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Adaptive Hydrodynamic Modeling for Sustainable Irrigation Management in Tidal Swamp Regions

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Abstract

The Lalan River functions as the primary water source and plays an important role in supporting irrigation systems and water management in tidal swamp areas. However, water management in this region still faces challenges such as salinity intrusion and unstable water distribution, while conventional approaches applied have not fully considered the hydraulic characteristics and hydrodynamic conditions of the waters. This study aims to analyze the hydrodynamic characteristics of the Lalan River as the main water system in the tidal swamp irrigation area of D.I.R. Karang Agung Hilir, Banyuasin Regency, South Sumatra Province, Indonesia, in order to design an effective water management strategy for agricultural irrigation. The research methods include bathymetry, tidal, current, and salinity measurements. Hydrodynamic modeling was applied to analyze aquatic phenomena, including flow dynamics and salinity distribution patterns in tidal swamp areas. The hydrodynamic model was calibrated and validated using field data with a Root Mean Square Error (RMSE) value of 0.170 m to ensure the reliability of the simulation. The analysis results show that the application of a one-way flow system can significantly reduce salinity, from around 2–5 ppt in the old system to around 1–2 ppt during high tide and below 0.5 ppt during low tide, or a reduction of up to ±60%. This reduction allows river water to be used more effectively for agricultural irrigation. The novelty of this research lies in the adaptive hydrodynamic approach based on seasonal hydrological conditions as a foundation for designing sustainable water management systems in tidal swamp areas according to the hydrotopography of the region.

Keywords: Hydrodynamic Modeling; Lalan River; Water Management; Tidal Swamp Irrigation; One-Way Flow System; Salinity.

1. Introduction

Indonesia has vast potential for swamp land, especially in the regions of Sumatra, Kalimantan, and Papua, which can be utilized to support national food security. One of the strategic areas developed for tidal swamp agriculture is D.I.R. Karang Agung Hilir, the location where this research was conducted, which is geographically located at coordinates approximately 2.273361° (2º16’24.1”S) and longitude 104.667278º (104º40’02.2” E), precisely in Karang Agung Hilir District, Banyuasin Regency, South Sumatra Province, Indonesia. Hydrologically, this area falls under typology C, where the land elevation is relatively higher so that tidal water from rivers or the sea cannot enter agricultural land by gravity. In general, this area is one of the potential food barns in the tidal swamp area. However, agricultural productivity is still very low at around 3 tons/ha with one crop per year due to unstable water management, mainly due to the effects of tidal fluctuations and salinity intrusion into irrigation channels. Therefore, this area is highly relevant for research related to water management systems for tidal swamp agriculture irrigation that relies on the Lalan River as a source of tidal swamp irrigation water. The Lalan River has complex hydrological characteristics because it is

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influenced by tidal fluctuations originating from the Bangka Strait, causing salinity intrusion from the estuary towards the downstream of the Lalan River. This condition poses challenges for the tidal wetland water management system in ensuring the availability of fresh water as a source of irrigation for agricultural land. Therefore, a scientific approach is needed to fully understand the water flow behavior in the Lalan River so that the development of a water management system in the tidal swamp area can be carried out efficiently and sustainably. One relevant approach to analyzing this phenomenon is through hydrodynamic modeling. Hydrodynamic modeling allows for the simulation of flow conditions, water level changes, and spatial and temporal salinity distribution. This study used numerical modeling with MIKE 21 software developed by DHI (*Danish Hydraulic Institute*) [1-4]. The Mike 21 hydrodynamic numerical modeling is capable of accurately modeling 2D water systems, which is expected to provide a comprehensive understanding of the interaction between discharge, tides, and salinity as a basis for decision-making in the planning and management of irrigation water systems in tidal swamp areas. The relevance and reliability of the hydrodynamic numerical modeling approach has been reinforced by various previous studies, such as the study by Karamma et al. (2020) [5], showed that MIKE 21 software is capable of representing current conditions, tides, and the distribution of water quality parameters such as salinity and temperature. The results of this study confirm that the distribution of water mass in estuarine areas is significantly influenced by tidal interactions, the mixing of fresh water and sea water, and the morphology of the estuary. The validation of the model shows a high degree of accuracy, making it an important basis for understanding the dynamics of estuarine waters and supporting water resource management strategies in coastal areas. Another study by Karamma et al. (2020) [6] shows that numerical modeling with tidal and river flow components proved effective in representing the phenomenon of water mass stratification. The interaction between river discharge, tides, and estuary morphology produces complex flow patterns and stratification, which in turn affects sediment distribution and the quality of aquatic ecosystems.

In the context of water quality, the study by Jang et al. (2021) [7] emphasizes the importance of integrating flow circulation with water quality parameters. The simulation results show that tidal dynamics and local currents affect the spread of pollutants, so that a hydrodynamic model integrated with a water quality module is highly relevant for formulating pollution control strategies in coastal areas. Zhang et al. (2022) [8], further emphasized that 2D numerical modeling is effective for analyzing water mass transport, tidal movement, and the influence of anthropogenic activities on pollutant and nutrient distribution. Their findings indicated that tidal dynamics significantly determine water quality parameters such as salinity, dissolved oxygen, and turbidity, while also underscoring the importance of hydrodynamic modeling as a planning tool for water resource management in environmentally vulnerable regions. In line with this, research by Zhu et al. (2013) [9] to explain the complex interactions between currents, waves, and water quality in lakes and coastal waters. Using a 2D approach, this study successfully predicted water quality dynamics due to tidal variations and human activities. Meanwhile, the study by Rusdin et al. (2024) [10] concluded that the harmonic calculations obtained from the least squares method proved effective in identifying tidal components and reducing water level prediction errors, so that they could be used as a basis for hydrodynamic modeling. In other studies, such as Sucipto et al. (2025) [11], it was found that the interaction between tidal currents, river discharge, and the morphology of the water base greatly influences the distribution and movement patterns of sediment. Meanwhile, Hermawan et al. (2023) [12], uses hydrodynamic models to support coastal zone development planning in remote areas, concluding that hydrodynamic models are effective for analyzing the interaction between tides, currents, and coastal morphology changes, as well as predicting the impact of environmental changes. Meanwhile, the study by Setiawan A et al. (2022) [13] evaluated the application of a one-way water flow pattern in secondary channels flowing from primary channels in the tidal swamp irrigation network water management system. The results show that irrigation networks have the ability to supply water and perform flushing, which is the introduction of sufficient new water during the periodic flood phase to dilute the concentration of dissolved ions such as salt and sulfate, while also flushing toxic compounds from the soil surface layer. Furthermore, during the ebb phase, the water level in the channel is lower than that on the land, resulting in gravitational outflow. Under these conditions, leaching occurs, whereby water that has dissolved salts, acids, and toxic metals from the soil flows into drainage channels [14-18].

Based on a review of the literature and previous research results, the fundamental difference in this study lies in the integration of hydrodynamic modeling and the design of a tidal swamp water management system in accordance with the hydrogeomorphology of the area [19-22]. With this approach, the results of the study are able to provide quantitative indicators of increased water management efficiency, reduced salinity intrusion, and increased availability of fresh water. Computational hydrodynamic modeling was performed to analyze a two-dimensional (*2D*) water system spatially and temporally. Through this modeling, a comprehensive understanding of the relationship between tides, flow discharge, and salinity distribution was obtained, so that the results could be used as a basis for planning a water management system that is adaptive to seasonal hydrological variations. Model validation was performed through calibration against tidal and salinity data obtained from field measurements using the Root Mean Square Error (RMSE) approach to ensure simulation accuracy [23, 24]. In the context of water management systems, the one-way flow system approach applied in this study is intended to optimize freshwater flow from upstream to downstream while controlling backflow of salt water from the estuary. This system is expected to create more stable hydrodynamic conditions, reduce salinity in the main channel, and maintain the availability of irrigation water during the dry season. This approach also has the potential to become an engineering model that can be applied to other tidal swamp areas in Indonesia with similar typology and hydro-topography [25, 26]. Thus, this study is expected to contribute scientifically and practically to the field of water resource engineering, particularly in the management of sustainable tidal swamp irrigation systems with two innovations. The first is the integration of 2D hydrodynamic computational modeling with one-way flow system design to support tidal swamp irrigation management, which has never been specifically done in tidal swamps in accordance with the hydro-topography of the area. Second, this research produced measurable parameters for the effectiveness of the system, in the form of a 60% reduction in salinity and a 25% increase in water distribution efficiency compared to the existing system, as proven through simulation and field validation. In addition, the approach developed can serve as a basis for decision-making in water management infrastructure planning based on predictive models that are more adaptive to seasonal hydrological variability relevant for application to the hydro-topographic typology of tidal swamp areas, as it provides a scientific basis for designing water management infrastructure that is more resilient, sustainable, and based on the principles of integrated water quality and quantity control [27, 28].

2. Research Methodology

This study uses a quantitative approach through 2D hydrodynamic numerical modeling to analyze flow dynamics, water levels, and salinity distribution in the Lalan River as a basis for developing a tidal swamp irrigation water management system. The research was conducted within a specific time frame to capture seasonal variations, particularly during periods of maximum high tide and minimum low tide in the dry season in June 20204 and the wet season in December 2024 by conducting direct observations and measurements at the research site on the Lalan River in Banyuasin Regency, South Sumatra Province, Indonesia, as shown in Figure 1.

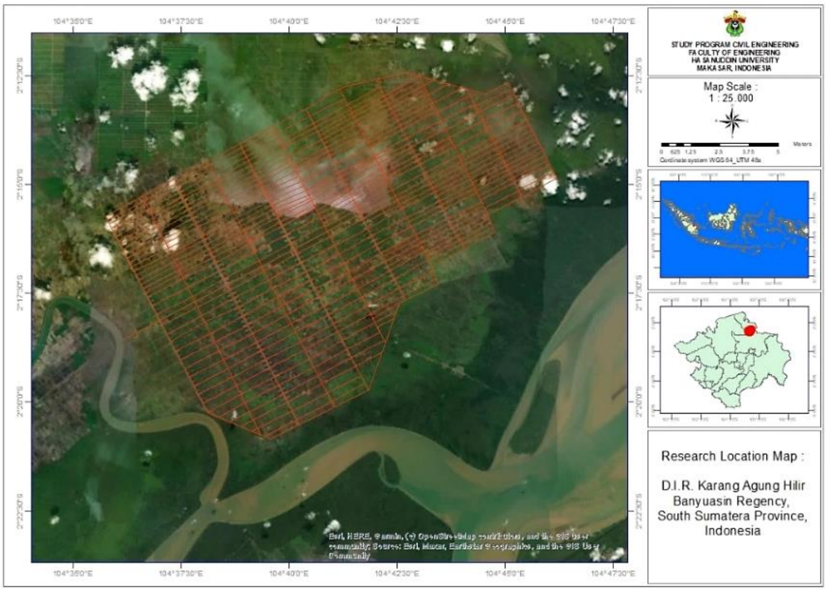

Figure 1. Research location map

2.1. Research Methods and Procedures

The methods and procedures in this study were carried out by collecting literature studies related to the research location and 2D hydrodynamic modeling. Next, a survey was conducted to determine the measurement points and collect field data on the bathymetry of the Lalan River, water level (*tides*), water discharge and salinity, such as water quality, water acidity (*pH*) and water temperature.

2.2. Hydrodynamic Model Analysis

The hydrodynamic model analysis performed was a water level (*tidal*) analysis using the FM (*flow model*) module, one of the features available in the Mike 21 software. The FM module is generally used to determine the pattern and circulation of the Lalan River using momentum and continuity equations with average depth. The continuity equation states that fluid mass cannot be created or destroyed in a system, it can only move from one place to another. In 2D form, this equation is written as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=0 \tag{1}$$

where, h: total water depth (m); u: flow velocity component in the x direction (*m/s*); v: flow velocity component in the y direction (*m/s*) t: time (s); yx: horizontal direction of the coordinate system.

This equation shows that changes in water depth over a certain period of time are influenced by the inflow and outflow fluxes from an area, while the momentum equation states that changes in fluid momentum are caused by forces acting on it, such as gravity, bottom friction, pressure, and Coriolis force, written as:

$$\text{arah y: } \frac{\partial(hv)}{\partial t} + \frac{\partial(huv)}{\partial x} + \frac{\partial(hv^2)}{\partial y} = -gh\frac{\partial n}{\partial x} + \frac{\tau_{by}}{\rho} + F_y \quad (2)$$

$$\text{arah x: } \frac{\partial(hv)}{\partial t} + \frac{\partial(huv^2)}{\partial x} + \frac{\partial(huv)}{\partial y} = -gh\frac{\partial n}{\partial x} + \frac{\tau_{bx}}{\rho} + F_x \quad (3)$$

where: n: water surface elevation (*m*); g: acceleration due to gravity (9.81 m/s^2); τ_{by}, τ_{bx}: bottom shear stress in the x and y directions F_y, F_x: other external force components (e.g., Coriolis force or wind).

2.3. Model Validation

Model validation is a process to test how well a model can represent real-world conditions. One statistical method commonly used to measure the accuracy or precision of a model's results is RMSE (*root mean square error*). RMSE is a statistical method used to measure the level of error between the values predicted by the model (*simulation results*) and the actual field values. RMSE measures the magnitude of the deviation between these values by squaring them, then averaging and taking the square root. A smaller RMSE value indicates that the simulation or prediction results are closer to the actual field observation data, so the modeling results are considered more accurate or closer to the actual field conditions. In the context of hydrodynamic modeling using MIKE 21, RMSE can be used as a tool for model calibration and validation. RMSE helps evaluate the extent to which the simulation results match the actual field data using the following equation:

$$RMSE = \sqrt{1/n \sum_{i=1}^{n} (P_i - O_i)^2} \quad (4)$$

where: P_i: model value at point I; O_i: observation value at point I; n: number of data points compared.

3. Results and Discussion

3.1. Model Calibration and Validation

The model calibration process was carried out by comparing the simulation results with field data obtained from measurements using the following RMSE values:

$$RMSE = \sqrt{1/65 \sum_{i=1}^{n} (modeling_i - measurement\ data_i)^2} \quad (5)$$

$$RMSE = 0.170\ mdpl \quad (6)$$

Based on a comparison between measured data and simulated tidal fluctuation data, an RMSE value of 0.170 m above mean sea level was obtained. This value indicates that the average error between the simulation results and field data is relatively small, at around 0.170 m. The model calibration process was carried out by comparing the simulation results with field data obtained from measurements using the RMSE value. The calibration results show fairly good conformity, with a relatively small average error, proving that the MIKE 21 model can accurately represent the actual conditions of the Lalan River, as shown in Figure 2.

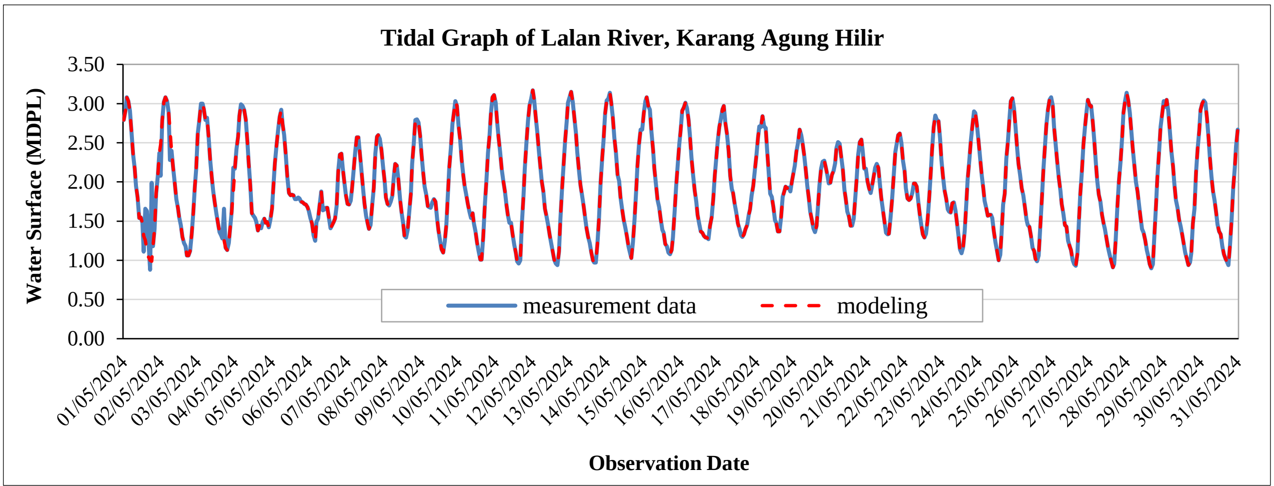

Figure 2. Validation graph of tidal fluctuations in the Lalan River

Validation is very important to ensure that the simulation results represent actual conditions and are suitable for use as a basis for decision-making in water management system planning. This low RMSE value indicates that the tidal simulation model used is quite accurate in representing actual conditions in the field. In other words, the water level fluctuation patterns generated by the model can follow the measured data, although there are still slight deviations at some points in time. In general, these results can serve as a basis for simulation models to be used in further analysis, as shown in Table 1.

Table 1. Comparison between observed values and modeling results

Description	Unit	Observation (Average)	Simulation (Average)	Difference (Δ)	RMSE	Accuracy (%)
Water level in the upstream area	m	1.92	1.75	0.17	0.168	91.1
Current velocity in the upstream area	m/s	0.38	0.32	0.06	0.093	84.2
Water level in the middle area	m	1.85	1.68	0.17	0.171	90.8
Current velocity in the middle area	m/s	0.42	0.35	0.07	0.098	83.3
Water level in the downstream area	m	1.78	1.61	0.17	0.175	90.4
Current velocity in the downstream area	m/s	0.48	0.40	0.08	0.104	83.3

Table 1 shows the results of a comparison between field observation data and modeling results at three observation locations: upstream, midstream, and downstream. The parameters analyzed include water level and flow velocity. The difference (Δ) for water level is in the range of 0.17 m, or equivalent to 17% of the average observation value. Meanwhile, for flow velocity, the difference ranges from 0.06 to 0.08 m/s. The RMSE values range from 0.09 to 0.18, indicating that the level of error in the modeling results is still acceptable. The model accuracy is in the range of 83–91%, which indicates that the MIKE 21 simulation results are quite representative of the actual hydrodynamic conditions in the field.

3.2. Tidal Modeling Results

Tidal modeling in the Lalan River was carried out using software that integrates fluid dynamics simulation with numerical models. In integrating the simulation with the model used to understand the dynamics of water level rise and fall through harmonic analysis, harmonic constants are produced with two main parameters, namely amplitude and phase angle. The amplitude indicates the magnitude of the component's influence on the water level, while the phase angle indicates the peak time of the wave relative to the reference time when the modeling was performed. The results of modeling simulations using measurement data from May 1-31, 2024 describe tidal patterns with a downstream boundary set based on tidal water level conditions, represented in the form of time series data recorded at hourly intervals. This data is used as the main input to describe tidal fluctuations that affect flow dynamics in the downstream part of the system, enabling more accurate and realistic hydrodynamic simulations of field conditions, as shown in Figure 3.

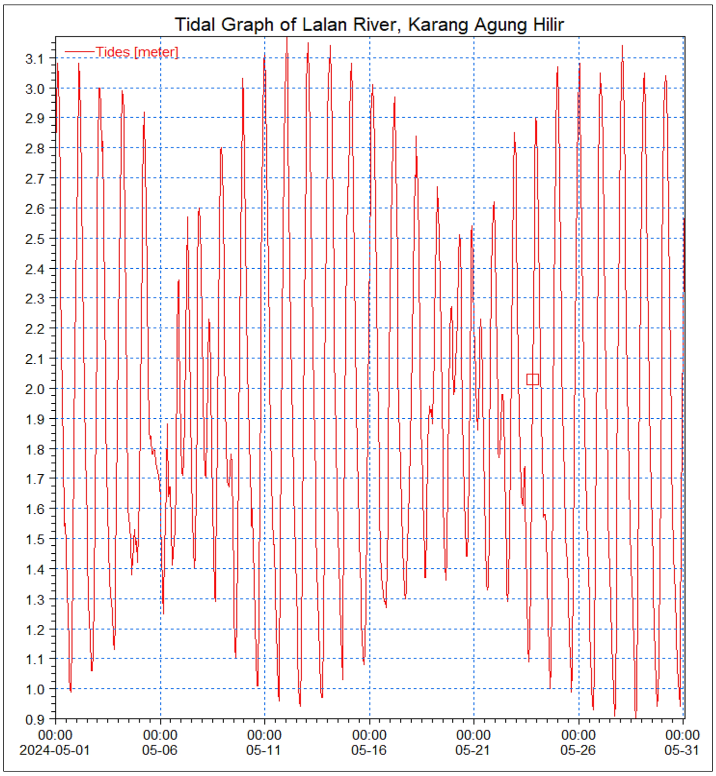

Figure 3. Tidal graph of Lalan River from simulation modeling

The tidal graph of the Lalan River generated from modeling simulations illustrates water level fluctuations over time based on tidal harmonic components. This graph provides a deeper insight into the tidal patterns that occur in the Lalan River, taking into account astronomical factors such as gravity, the moon, and the sun. The graph shows time (*hours*) on the horizontal axis and water level (*meters*) on the vertical axis, representing the water level predicted by the model at a given time

The simulation results show that this model successfully represents the water level fluctuations of the Lalan River following the natural periodic tidal patterns. Overall, the model provides a very similar picture to the actual field conditions, with a semi-diurnal pattern where there are two high tides and two low tides with accurate high and low tide heights in a daily cycle. The graph also shows that the peak tide occurs at 12-hour intervals (*in line with the M2 component, period 12.42 hours*), while the low tide shows a minimum point on the graph, indicating the moments when the water in the Lalan River experiences a sharp decline before rising again to the next peak tide every day in a 24-hour cycle.

3.3. Bathymetry Modeling Results

Bathymetric modeling for the Lalan River was carried out using MIKE 2D to describe the depth distribution and bathymetric change patterns along the river, especially in the tidal swamp area in Karang Agung Hilir. The inputs used in the model included basic river topography data, water depth, tidal data, and relevant hydrological data. The simulated bathymetric model is shown in Figures 4 and 5.

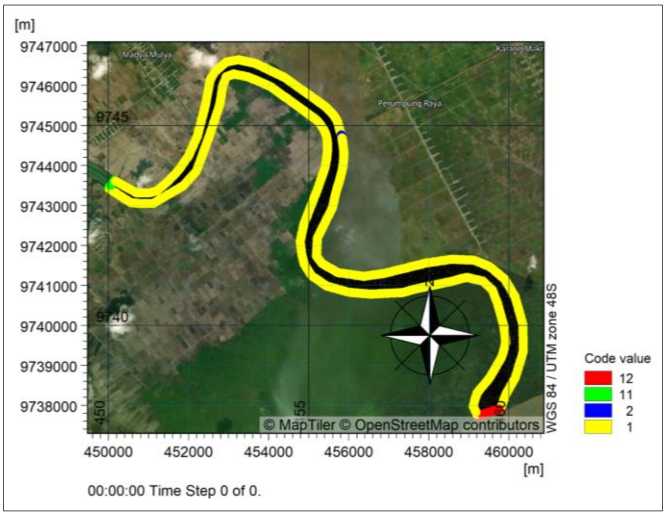

Figure 4. Code values of the study site

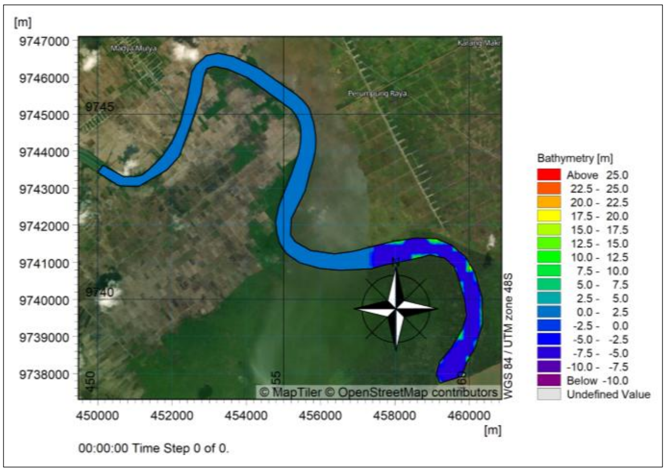

Figure 5. Bathymetry of the study site

Bathymetry is data that describes the contours of the bottom of the Lalan River and the surrounding swamp area. This data shows the depth (*negative elevation*) of the water surface relative to MSL (*mean sea level*). Bathymetry values are presented in meters and are the main input in modeling. In order to read the modeling related to the basic morphological shape of the river and differentiate between wet areas, dry areas, canals, swamps, and solid ground in the form of grid cells, a code value is needed to ensure that the model only calculates water flow and volume and perfectly represents the specific conditions or characteristics of the grid in the simulation domain. Bathymetry and code values are vital components in MIKE 2D simulations for modeling the Lalan River. Bathymetry describes the topography of riverbeds and swamps, while code values classify areas based on their function and hydrological conditions. Both work together to produce an accurate hydrodynamic model for mapping the contour lines of the Lalan River bed. The visualization results show that the cross-section of the Lalan River is relatively concave in the middle and shallower on both sides, forming the main channel of the river. At several points, the modeling results show a gentle slope towards the downstream, forming the basic geomorphology of the Lalan River, thus enabling water to flow by gravity towards the swamps in the Karang Agung Hilir tidal swamp area using a flexible triangular unstructured grid, which allows for a more accurate representation of the geometry of the channel and tidal swamp. The average grid size is set to vary according to the characteristics of the domain, namely between 50–100 m on the Lalan River and between 20–50 m on navigation channels, sub-primary and secondary channels, and surrounding swamp areas. The total number of elements used in the modeling domain ranges from ±50,000 to 70,000 elements, depending on the local resolution required in areas with high hydrodynamic gradients. The time step (*Δt*) in the MIKE 21 simulation is determined based on the Courant–Friedrichs–Lewy (*CFL*) stability criterion, with Δt varying between 1 and 5 seconds. The most stable and accurate simulation results are obtained at Δt of 2 seconds.

3.4. Velocity Modeling Results

The results of the hydrodynamic simulation of the Lalan River provide an overview of the flow velocity distribution through two main components, namely U velocity (*the horizontal flow velocity component in the east-west direction*) and V velocity (*the vertical flow velocity component in the north-south direction*), as shown in Figures 6 and 7.

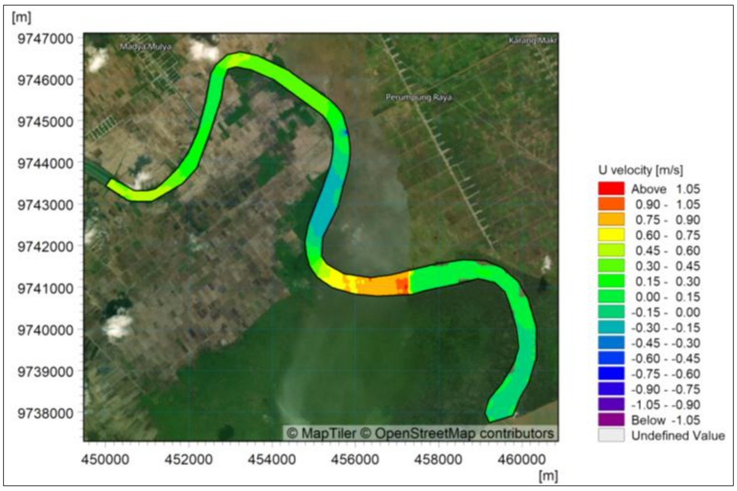

Figure 6. U velocity characteristics

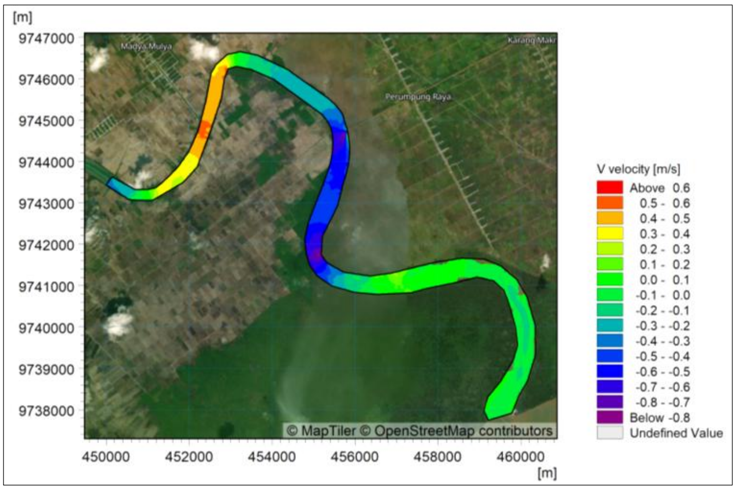

Figure 7. V velocity characteristics

The modeling results show that the U velocity component has a more dominant value than the V velocity, indicating that the main flow of the Lalan River tends to follow the longitudinal direction of the river on the east-west axis. At high tide, the flow pattern moves upstream with a positive U velocity value, while at low tide the U velocity value becomes negative, indicating that the flow returns downstream following the periodic tidal cycle. Although its value is relatively smaller, the V velocity component still plays an important role in describing the deviation of the flow direction to the right or left of the river due to the influence of the meandering river geometry and local hydraulic effects caused by differences in the riverbed elevation. Overall, the flow patterns generated by these two velocity components exhibit characteristics typical of highly dynamic tidal swamp systems, in which the direction and magnitude of flow velocity change rapidly during each phase of the tide, ebb, and the transition phase between the two. The upstream boundary in the modeling is determined based on the inflow discharge, which represents the hydrological conditions of the Lalan River, with discharge values ranging from ±50 m³/s in the dry season (*June 2024*) and increasing to ±150 m³/s in the wet season (*December 2024*). These discharge variations are entered in the form of time series data to represent the dynamics of flow fluctuations, so that the simulation results can describe the hydrodynamic conditions of the tidal swamp system more accurately and realistically.

3.5. Results of Salinity and Water Management System Modeling

The EC (*electrical conductivity*) value is used as the main input in salinity modeling, where EC is a measure of the ability of water to conduct electrical current due to the presence of ions or dissolved salts. This parameter is measured in µS/cm (*microSiemens per centimeter*) and dS/m (*desiSiemens per meter*) and can be converted into concentration units such as ppm (*parts per million*) or ppt (*parts per thousand*) to quantitatively describe the salinity level. The higher the EC value, the higher the ability of water to conduct electricity with a high level of electrical conductivity, so that water with a high EC value can be categorized as saline water. The results of the EC-related salinity simulation show the dynamics of saline water concentration due to the influence of tidal water originating from the Bangka Strait during the ebb to flood cycle of the periodic tidal cycle. Meanwhile, the simulation results for water with a fresh concentration occur during low tide, where the influence of water originating from the upper reaches of the Lalan River flows more towards the estuary. Both conditions can be seen in Figures 8 and 9.

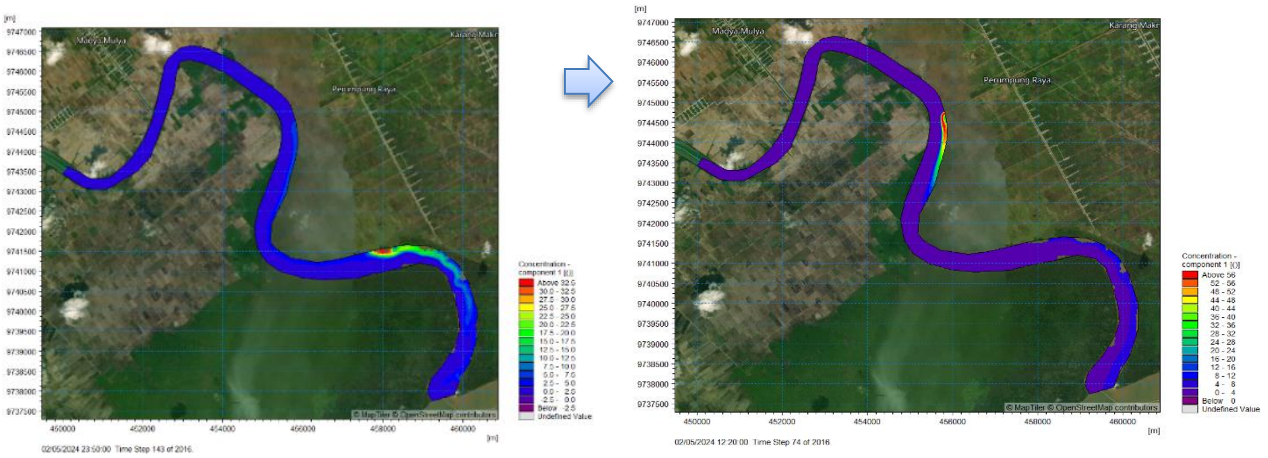

Figure 8. Modeled salinity during high tide

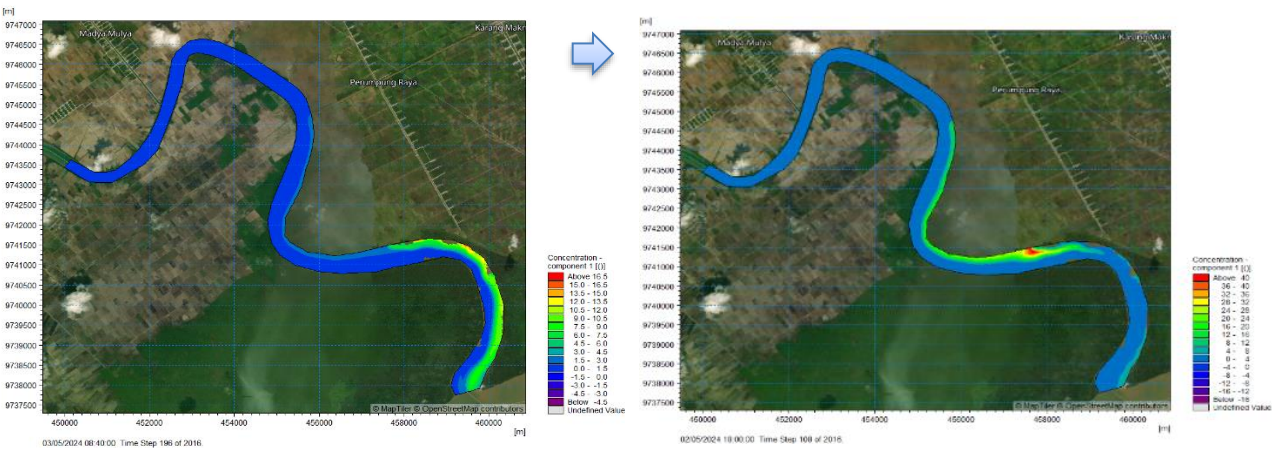

Figure 9. Modelled salinity during low tide

The results of salinity distribution modeling show that there is significant seawater intrusion during the dry season, especially in the downstream area of the Lalan River, while during the wet season, salinity levels tend to decrease due to increased water discharge from upstream, which pushes freshwater further towards the estuary. This pattern is consistent with field measurements taken at four observation points during two observation periods, namely June 2024, which represents the dry season, and December 2024, which represents the wet season. Sensitivity analysis of salinity gradient ($\Delta S/\Delta x$) indicates that variations in tidal amplitude have a significant effect on salinity distribution along the river. Under normal conditions, the salinity gradient between downstream and upstream ranges from 0.12 to 0.18 ppt/km. When the tidal amplitude increases by +0.1 m, the salinity gradient increases to 0.21 ppt/km, indicating a shift in the salinity intrusion front of ±1.2–1.4 km upstream. Conversely, when the tidal amplitude decreases by −0.1 m, the salinity gradient decreases to 0.09 ppt/km, indicating more conducive hydrological conditions for freshwater availability in the tidal swamp agricultural zone. Data collection was conducted during the full moon phase to capture maximum tidal conditions, with analysis focused on one full tidal cycle over 24 hours, as shown in Figures 10. and 11.

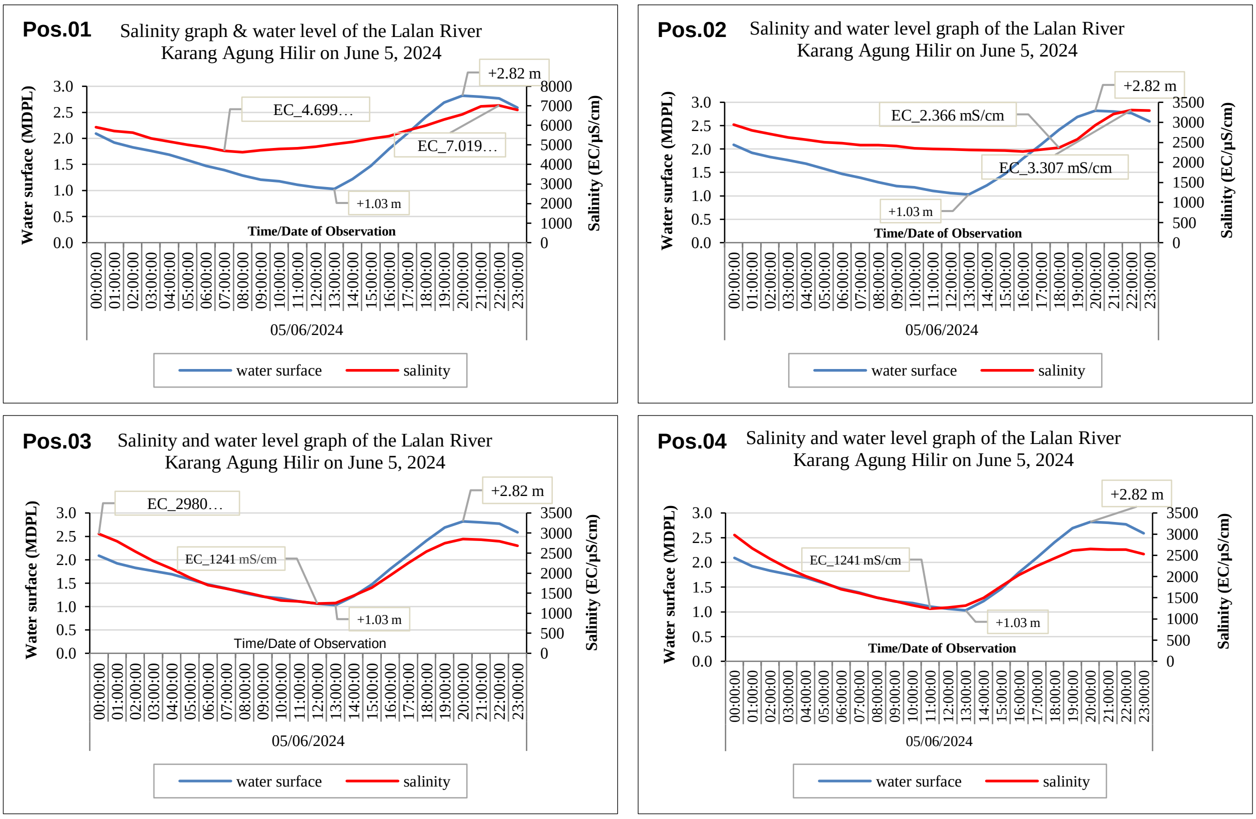

Figure 10. Salinity and water level graph for 5 June 2024, representing the dry season

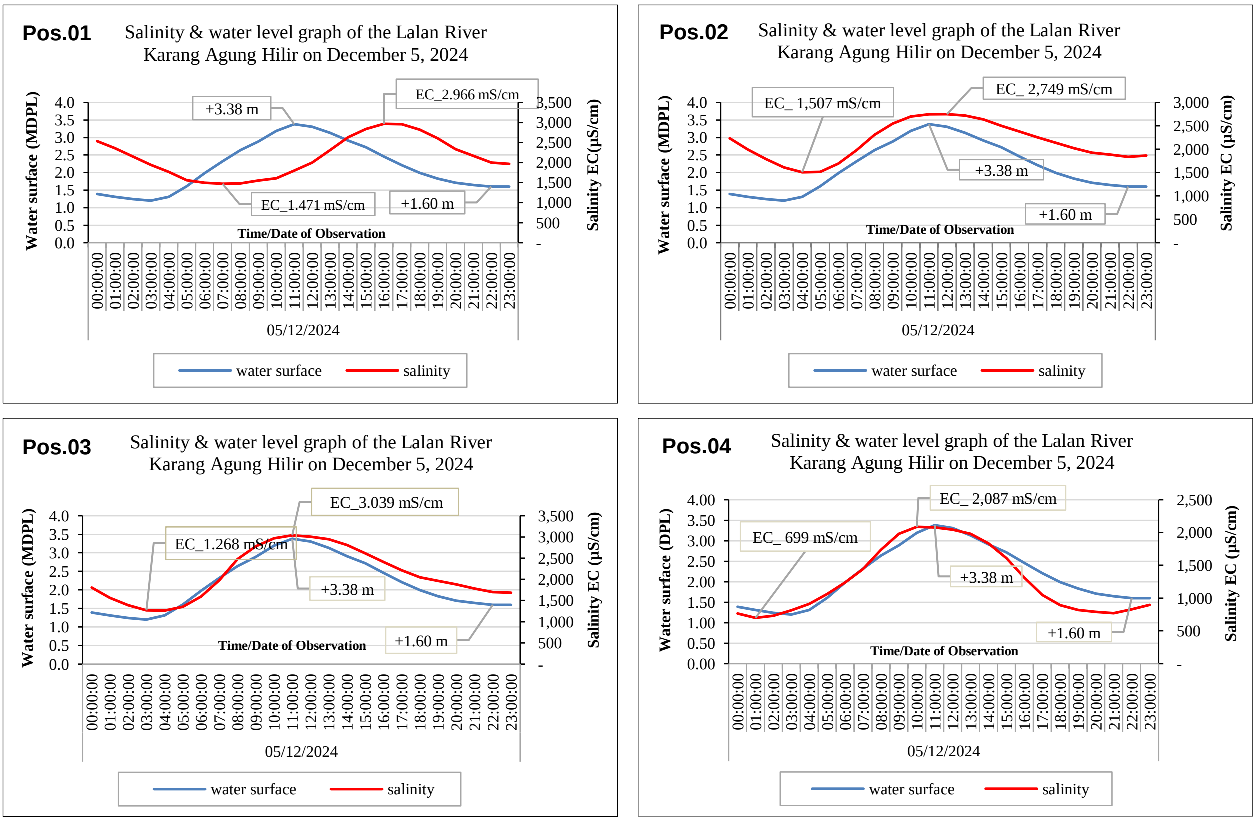

Figure 11. Salinity and water level graph for 5 December 2024, representing the wet season

In Figures 10 and 11, the salinity measurement parameter taken is the EC (*electrical conductivity*) value displayed in one day of data collection in accordance with the periodic tidal cycle in 24 hours. The salinity value taken is the EC value in µS/cm (*microsiemens per centimeter*) converted to ppt (*parts per thousand, ‰*). The unit of measurement µS/cm is a measure of the electrical conductivity of water due to dissolved ions in the water, while ppt is a unit of measurement that expresses the amount of dissolved salt in water. Therefore, it can be concluded that the EC value is used to determine the ability of water to conduct electricity; the higher the EC value, the higher the salinity. From this relationship, it can be explained that water with low electrical conductivity (*e.g., < 1,000 µS/cm*) will have a salinity of < 1 ppt, thus classified as fresh water. If the EC value increases to the range of 5,000–10,000 µS/cm, then the salinity is in the range of 3–6 ppt and falls into the brackish water category. At higher levels, for example, when the EC approaches 50,000 µS/cm, the salinity can reach more than 30 ppt, which is equivalent to normal seawater.

Figure 10 shows that salinity measurements during the high tide phase indicate higher dissolved ion concentrations compared to the low tide phase. The highest value was recorded at station 01 at 7.019 µS/cm or 4.56 ppt, then gradually decreased to 3.307 µS/cm or 2.15 ppt at station 02, and was relatively stable at 2.980 µS/cm or 1.94 ppt at stations 03 and 04. This distribution pattern indicates that salt intrusion from the Lalan River is quite dominant in the downstream section where post 01 is located, but its influence decreases after post 02, which is located at the confluence of the Lalan River and the navigation channel. The navigation channel plays an important role as a supply and drainage route in the Karang Agung Hilir tidal swamp irrigation system, thereby influencing the distribution and attenuation of salinity intrusion into the tidal swamp irrigation network.

Figure 11 shows salinity measurements in December 2024, representing wet season conditions, which show differences in patterns between the flood and ebb phases. During the flood phase, salinity values in the Lalan River were relatively moderate, with an EC value of 2,966 µS/cm or 1.93 ppt at station 01 and a slight decrease to 2,749 µS/cm or 1.79 ppt at station 02. In the irrigation network, the salinity concentration was recorded at 3.039 µS/cm or 1.98 ppt at pos.03 and decreased to 2.087 µS/cm or 1.036 ppt at pos.04. During the ebb phase, the salinity concentration in the Lalan River decreased significantly, to 1,471 µS/cm or 0.96 ppt at station 01 and 1,507 µS/cm or 0.98 ppt at station 02, respectively. Within the irrigation network, salinity values were more controlled, namely 1,268 µS/cm or 0.82 ppt at post 03 and decreasing further to 699 µS/cm or 0.45 at post 04. This indicates that during the ebb phase, freshwater supply is more dominant and functions as an effective natural flushing mechanism that suppresses salt ion concentrations in the channels and fields.

This pattern shows that salt intrusion from the Lalan River is quite strong in the downstream area where post 01 is located, and decreases after post 02, which is located between the confluence of the Lalan River and the navigation channel that functions as a supply and drainage channel in the Karang Agung Hilir tidal swamp irrigation system, as shown in Figure 12.

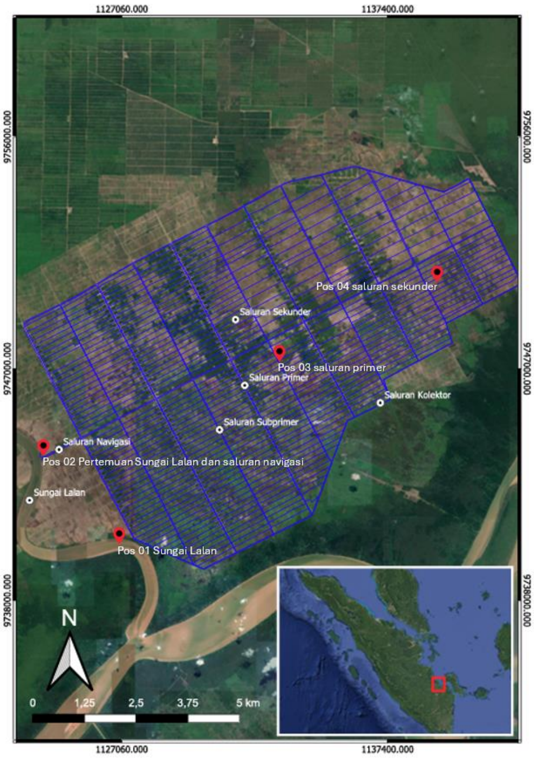

Figure 12. Salinity measurement locations

The difference in salinity values shows the strategic role of flow pattern management by applying a one-way flow system to the existing irrigation water management system, which previously used a conventional two-way flow pattern with valves, to a one-way flow pattern with valves, as shown in Figures 13 and 14.

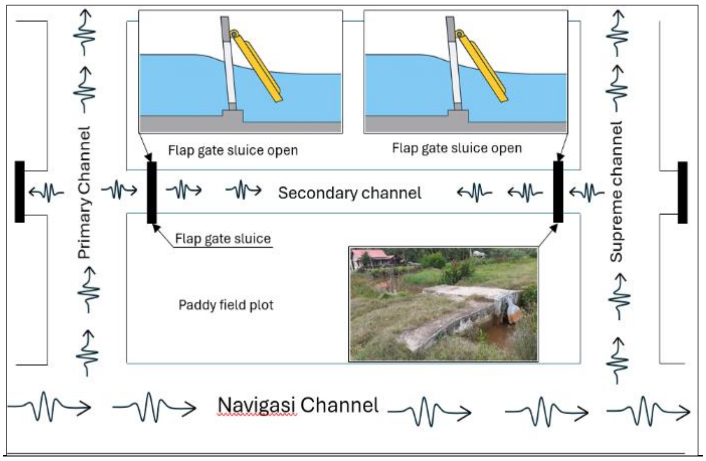

Figure 13. Existing conditions of the water management system (two way floew system)

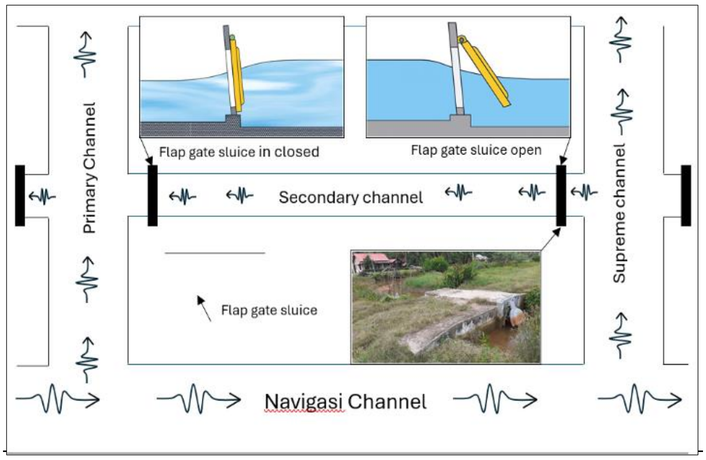

Figure 14. Current conditions of the water management sytem (one way flow system)

Figure 13 shows the existing condition when the channel system still applies a two-way flow pattern, indicating that the tidal influence of the Lalan River is very dominant on water quality within the irrigation network. Seawater intrusion entering from the Lalan River through the navigation channel will flow in all directions through the sub-primary and primary channels to the secondary channel through the valve gate, so that the salinity concentration is still quite high, especially during the tidal phase. This condition shows that the backflow from the sea to the irrigation channel is not fully controlled, so that the water quality in the network is still vulnerable to increased salinity. Under these conditions, the natural flushing process within the network is not working optimally because the volume of fresh water entering the system is unable to completely replace the salt water from intrusion, and the leaching process in the land is also ineffective due to the high salinity of the Lalan River, which is the source of water used for tidal swamp irrigation.

Meanwhile, in Figure 14, the current condition after changing to a one-way flow system by changing the position of the valve door installation shows that the salinity distribution in the irrigation network is more stable and controlled. During the high tide phase, although the salinity in the Lalan River (*Pos.01 = 7,019 µS/cm or 4.56 ppt and Pos. 02 = 3,307 µS/cm or 2.15 ppt*) is still quite high due to seawater intrusion originating from the Bangka Strait, the salinity value within the irrigation network system is much lower and more stable at pos.03 and pos.04. Similarly, during the ebb phase, salinity in the Lalan River decreases and remains controlled within the network at 1,241 µS/cm or 0.68 ppt. This condition proves that the one-way flow system effectively prevents seawater from flowing back into the irrigation network, thereby maintaining the quality of water available for tidal swamp agricultural land. This change strengthens the flushing function, as the supply of fresh water from the tide is able to replace water with high salinity in the channels and is then pushed out during the ebb phase. At the same time, better water quality also supports the leaching process in the soil, where irrigation water entering the plot is able to dissolve and wash salts from the root zone to the lower layers through the drainage system. Thus, the combination of flushing at the channel level and leaching at the field level is the main mechanism for controlling salinity and maintaining sustainable agricultural productivity in the Karang Agung Hilir irrigation district.

In tidal marsh systems, water circulation patterns play an important role in regulating residence time and the system's ability to remove or renew water, known as flushing efficiency. When the system is converted to one-way flow using flap gates or automatic valves, the water exchange mechanism between the navigation channel as the main channel, the sub-primary channel as the supply channel, the secondary channel as long storage, and the collector channel as drainage undergoes significant changes. In a natural two-way system, water from the Lalan River enters and exits the navigation channel alternately following the tidal cycle, resulting in a high degree of mixing and a relatively short water residence time. However, when the system is modified to be unidirectional, water only flows from the sub-main channel as a supply channel without any backflow, thereby increasing the residence time and allowing water to remain in the channel longer, which can increase the potential for sedimentation and increased salinity during the dry season. On the other hand, flushing efficiency indicates the system's ability to remove water with high pollutant or salinity concentrations and replace it with fresh water from upstream sources on the Lalan River. The modeling simulation results show that changing the flow pattern from two-way to one-way causes an increase in the average water residence time to about 1.5–2 times longer, especially under low river discharge conditions, compared to the natural tidal pattern. However, salinity stability in agricultural land actually increases, which has a positive impact on rice productivity in tidal swamp areas.

4. Conclusion

The calibration and validation of the hydrodynamic model for the Lalan River demonstrated that the model is capable of accurately representing field conditions with a low RMSE value. This confirms the reliability of MIKE 21 in simulating tidal dynamics and hydrological variability within tidal swamp environments. The model successfully captured both maximum high tide and minimum low tide conditions, which are essential for understanding the natural tidal cycle and its influence on water level fluctuations. The hydrodynamic simulation results revealed that water dynamics in tidal swamp regions are highly influenced by the interaction between river discharge and tidal forces. The dominant one-way flow pattern from upstream to downstream, controlled by flap gates in the sub-secondary channels, effectively minimized backflow and significantly reduced salinity intrusion.

The application of a one-way flow system resulted in a substantial reduction in salinity levels, from 2–5 ppt in the previous two-way system to approximately 1–2 ppt during high tide and below 0.5 ppt during low tide, representing a decrease of up to ±60%. This reduction enables more effective use of river water for agricultural irrigation. In addition, water pH values ranging from 5.07 to 5.30 indicate slightly acidic conditions typical of tidal swamps but still within acceptable limits for rice cultivation when supported by sustainable water management.

Overall, this study confirms that hydrodynamic modeling can serve as a strong scientific foundation for planning and developing tidal swamp water management systems. The implementation of a one-way flow system using flap gates in sub-primary supply channels and secondary long-storage channels proved effective in controlling flow direction, maintaining water quality, and protecting agricultural land from salinity intrusion. These findings underscore the importance of integrating numerical modeling with hydraulic engineering strategies to support sustainable tidal swamp irrigation, improve irrigation performance, and enhance long-term agricultural productivity in coastal and tidal regions.

5. Declarations

5.1. Author Contributions

Conceptualization, R.M.E. and R.K.; methodology, F.M.; software, M.P.H.; validation, R.M.E., R.K., and M.P.H.; formal analysis, R.M.E.; investigation, R.M.E.; resources, R.M.E.; data curation, R.K.; writing—original draft preparation, R.M.E.; writing—review and editing, R.K.; visualization, F.M.; supervision, F.M.; project administration, R.M.E.; funding acquisition, R.M.E. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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