The Leaching Process of Acid Sulphate Soil by One- and Two-Way Flow Systems in the Katingan Swamp Irrigation Area

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Abstract. The Katingan Swamp Irrigation Area, established in 1980, has an important role in supporting food security in Indonesia. It needs to be reclaimed to increase agricultural production, especially for leaching acid sulphate soil. The swamp irrigation area was expanded and rehabilitated so that the two-way flow became a one-way flow system to support the leaching process. This study aims to assess the discharge and water quality alterations in the Katingan main channel after the change of flow system. The aim is achieved by comparing the outcomes obtained from one-way and two-way flow simulations. The simulation used a mathematical model based on water level, water quality, and land topography data collected in the field. According to the findings, the two-way system demonstrates that fresh water from the river has not been able to improve water quality (pH) at the end of the primary channel, thereby leading to extreme acidity in those regions. Meanwhile, a one-way flow facilitates efficient circulation and delivers fresh water to the farthest service regions. Effective water circulation is important to enhance water quality in agricultural areas that have recently expanded. The current study focuses on mid-irrigation. Future research may cover the entire irrigation network for in-depth analysis.

1 Introduction

The Katingan Swamp Irrigation Area, established in 1980 as part of a tidal swamp development initiative for the transmigration program, holds significant importance within the agricultural sector of Central Kalimantan. This region holds significant importance in ensuring food security in Indonesia since it is recognized as one of the top four rice producers within the province [1]. The agricultural sector in the Katingan Swamp Irrigation Area plays a crucial role in both national rice production and the local economy, serving as a primary source of income for numerous people in the surrounding area.

Over time, there has been an increasing emphasis on achieving Sustainable Development Goals (SDGs), leading the government and relevant stakeholders to prioritize enhancing irrigation networks and constructing infrastructure in the Katingan swamp irrigation area. The implementation of this progressive measure is crucial for the attainment of sustainable and effective water resource management. Implementing enhanced irrigation networks and constructing infrastructure have facilitated the ability to fulfill irrigation water requirements, manage water quality, and eventually increase agricultural production.

The Katingan area encounters several obstacles concerning tidal swamp land, mostly on water quality issues. These concerns encompass the presence of acidity from peat water and water originating from acid sulphate soil. This phenomenon occurs due to the region's proximity to peat forests and location close to coastal seas. Given the diverse composition and properties of the water within the area, this situation introduces inherent intricacy in managing water resources.

This condition further emphasizes the necessity of implementing measures to control the direction of water flow, as regulating water flow has proven to be the most effective and efficient method for enhancing water and soil quality in acid sulphate soils [2, 3]. Directed water flow allows enhanced regulation of interactions among diverse water characteristics, including brackish water intrusion during the dry season, peat water, and water from acid sulphate soils [4]. This measure will facilitate the efficient utilization of water resources and address complex challenges associated with the management of tidal swamp land in the Katingan region.

From its initial development till the year 2021, the Katingan swamp irrigation area has lacked water control facilities that provide the deliberate regulation of water flow. Consequently, the two-way water flow hinders the optimal functioning of acid water leaching. The alternating water flow pattern poses challenges in effectively managing the irrigation water quality, particularly in mitigating the adverse effects of high acidity levels that can potentially be detrimental to plant growth. The government developed plans to implement initiatives aimed at enhancing and rehabilitating the Katingan irrigation network in 2022. The proposed actions involve expanding the irrigation service area, increasing its coverage from 5351 to 10617 hectares. In addition, water management infrastructures were

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constructed, and efforts were made to rehabilitate channels to establish a one-way water circulation system.

Prior research on water flow in swamp irrigation systems has revealed notable disparities between one-way and two-way flow. The findings of the study conducted in the Terantang swamp irrigation area [5] indicate that the implementation of one-way flow control is more efficient in managing the distribution of irrigation water and enhancing water quality by decreasing the levels of iron concentrations within the network, as compared to the utilization of two-way flow.

Similar research has also been conducted in the Barambai swamp irrigation area [4]. Bidirectional flow, characterized by the back-and-forth movement of water, must be improved to ensure the consistency and quality of water flow, particularly in the context of acid water flushing. Insufficient water circulation and the accumulation of acidity at the end of the channel make the flushing procedure inefficient in dissolving and diluting acidity and toxicity.

Another study conducted in the Belanti swamp irrigation region included the implementation of a simulation that shifted the flow of water from two directions into one direction channel through the utilization of flap gates and weir structures [6]. The findings indicate that flap gates facilitate a more streamlined water flow into the drainage channel. Additionally, the weir structure enables a greater influx of fresh water into the system network, supporting the leaching process and acid removal.

The findings of previous studies offer a robust foundation for considering improvements to the water management system to transition the flow from bidirectional to unidirectional in the Katingan Swamp Irrigation Area. This study aims to conduct a flow analysis for both two-way and one-way systems utilizing a flap gate in the Katingan Swamp Irrigation Area. The investigation will focus on quantifying the volume of water flow and modeling its impact on water acidity (pH).

2 Methods

2.1 Study area

The Katingan swamp irrigation area is situated in the coastal area and encompasses a tidal-influenced swamp adjacent to peat forests. Katingan has gained recognition as a prominent rice-producing area in Central Kalimantan due to its abundant water resources, essential for agricultural activities. The local populace mostly relies on farming as their major source of living [1].

The main focus of this study is to examine the middle area of the irrigation system in the Katingan swamp irrigation area, encompassing both pre-existing and recently reclaimed land. The analysis was conducted from the primary channel close to the Katingan River to the end of the primary channel adjacent to the peat forest. The entire length of the channel was 8 kilometers, covering a service area of 785 hectares of rice fields (Fig. 1).

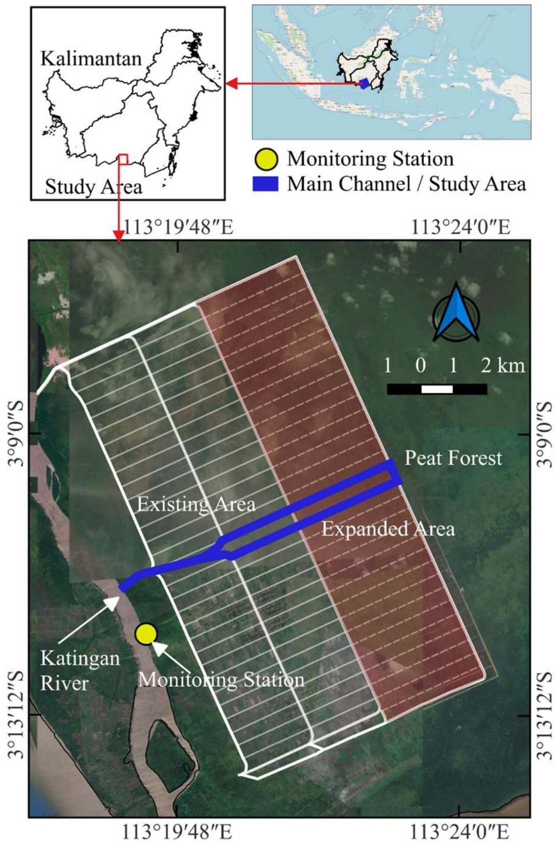

Fig. 1 Location of Katingan I lowland irrigation area (Modified with QGIS 3.32.1)

2.2 Data collection

A monitoring station to record water level and water acidity was installed on the Katingan River, as shown in Fig. 1. In the Dadahup swamp irrigation region [7], the use of data recorders with sensors for collecting water level and acidity has been previously employed. The difference is that the installation at Dadahup is permanent and equipped with a cloud system that permits access from anywhere via the Internet. Meanwhile, data collection at the Katingan research site must be done manually because the installation is semi-permanent and yet to be connected to the Internet. Fig. 2 displays water level measurements and acidity data from December 22, 2022, to January 1, 2023. Changes in water level and acidity recorded by data loggers are influenced by tidal energy. The water level rises at high tide, and water tends to approach neutral values. On the other hand, the water tends to be more acidic at low tide.

In addition to acquiring primary data through direct field collecting, secondary data collecting methods have significance in the modeling of water flow. Incorporating topographical data, including land elevation and water channel dimensions, plays an important part in the modeling procedure, allowing a comprehensive and accurate depiction of water flow patterns within the given area. The secondary data was obtained from the Kalimantan River Basin Organization II.

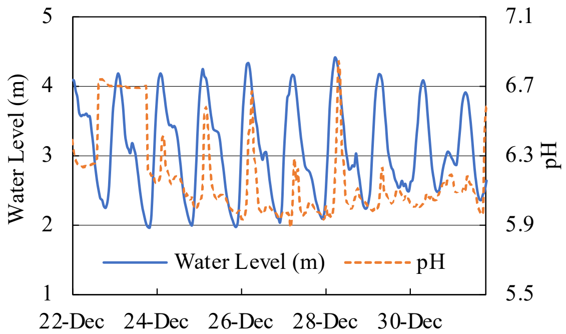

Fig. 2 Water level and pH recordings from data loggers at the Katingan River

2.3 Hydraulic simulation

Hydraulic simulation was performed using the Hydraulic Engineering Centre-River Analysis System (HEC-RAS) version 5.0.7 [8]. The simulation procedure included the development of a model of the irrigation network in the Katingan. This model incorporated primary and collector channels and the current land elevations derived from topographic maps. The model was formulated as a one-dimensional unsteady flow model. The geometric configuration of land or rice fields was considered inefficient due to its limited effectiveness in facilitating water flow. The Manning roughness coefficient value for the channel was 0.025 because the channel was considered clean and straight after rehabilitation. Meanwhile, the Manning roughness coefficient value for inefficient areas was 0.075 because rice vegetation and shrubs were along the downstream primary channel [9]. The dimensions of the primary and collector channels were determined according to the basic design specified in the planning of the Kalimantan River Basin Organization II (Fig. 3).

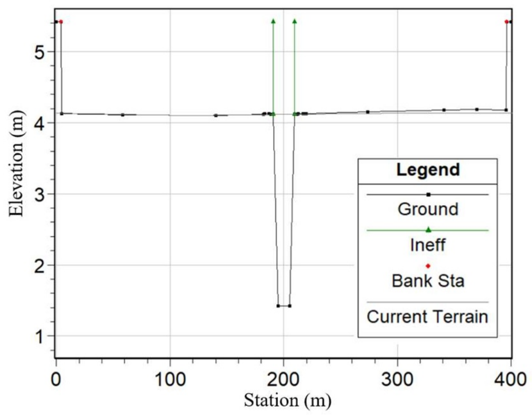

Fig. 3 Primary channel dimensional geometry

The simulation was carried out with two scenarios. In the first scenario, the simulation was run by adopting existing conditions, where the water flow has not been regulated and is allowed to flow with two-way water flow (Fig. 4). In the second scenario, the inclusion of flap gates serves to control the direction of flow, as seen in Fig. 5. Flap gates are designed to regulate the flow of fluid in a manner that permits only forward movement while preventing any backward or reverse flow. The flap gates were set to open when the water level reached 3.6 m, facilitating freshwater entry and removing the remaining water from the channel. Subsequently, the gates close once the water level reverts to 3.6 m to keep the water level at 3.6 m.

Subsequently, a comparative analysis was conducted on the simulation results of the first and second scenarios, focusing on the discharge and acidity levels, both in broad terms and with special emphasis on the A, B, and C locations. Point A is situated on the right primary channel, positioned at a distance of 4.1 km from the Katingan River. Point A was selected as a representative site close to the river. Subsequently, point B is situated on the left primary channel at a distance of 6.8 km from the Katingan River. Point C is within the collector channel, 8.3 km from the Katingan River. It is noteworthy that Point C represents the furthest place from the Katingan River. B and C points were selected based on their proximity to peat forests and distance from the Katingan River, resulting in high acidity levels in these areas [10].

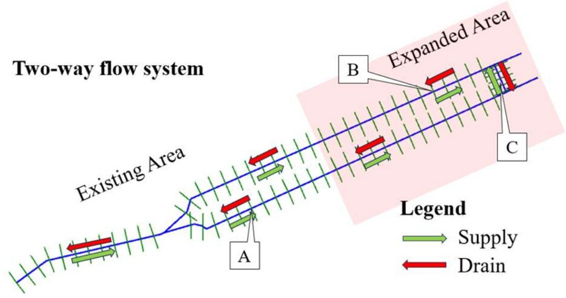

Fig. 4 Two-way flow system

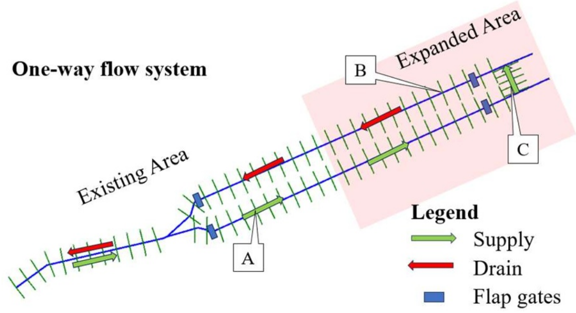

Fig. 5 One-way flow system

Boundary condition data is a needed component in the simulation process. The current study utilizes data logger recordings in the river to establish boundary conditions for the primary channel segment intersecting with the river. The dataset comprises water level data used for hydraulic analysis and pH data employed for water quality simulations. In addition to the considerations mentioned above, the simulation of water quality necessitates the inclusion of initial condition data. The initial conditions for all channels are established at a pH of 3.5 due to acid sulphate soil and peat water in the land. Proper calibration of the dispersion coefficient is crucial in water quality simulation. The dispersion coefficient is an important parameter that exerts control over the extent to which chemicals are dispersed and transported throughout water systems [11]. The dispersion coefficient in this study was calibrated using the automated tools available in HEC-RAS software.

The dispersion coefficient in the model is mathematically represented by Equation 1 and Equation 2 [12].

$$\mathbf{D = m\,0.011\frac{u^2w^2}{yu^*}} \quad (1)$$

$$\mathbf{u^* = \sqrt{gdS}} \quad (2)$$

In this equation, m represents the designated multiplier, u stands for face velocity in meters per second (m/s), w denotes the average channel width in meters (m), y represents the average channel depth in meters (m), u* signifies shear velocity in meters per second (m/s), g represents the gravitational constant at 9.81 m/s², d represents the average channel depth in meters (m), and S stands for friction slope.

The derived dispersion equation is rooted in Fischer's [12] formula. Fischer's equation, which does not incorporate a multiplier, assesses shear flow dispersion based on hydraulic and geometrical factors such as velocity, channel dimensions (width and depth), and slope.

The acidity levels of water are divided into several categories. Table 1 provides the categories of water acidity levels, specifically based on pH [13].

Table 1 Water acidity levels based on pH **[13]**

pH	Categories
< 3.5	Ultra acid
3.5 ~ 4.4	Extremely acid
4.5 ~ 5.0	Very strongly acid
5.1 ~ 5.5	Strongly acid
5.6 ~ 6.0	Moderately acid
6.1 ~ 6.5	Slightly acid
6.6 ~ 7.3	Neutral
7.4 ~ 7.8	Slightly alkaline

3 Results and Discussion

3.1 Results

The flow that has been implemented in Katingan is a two-way flow system. Fig. 6 displays the outcomes of water quality simulations with two-way flow. During the peak tide, areas located within a radius of 7 km from the Katingan River exhibit favorable water quality conditions characterized by a pH level exceeding 5.5. Subsequently, the pH values decline until they reach a value of 3.5 at the farthest area. There appears to be a notable water quality disparity between high and low tide. The occurrence of low tide is associated with elevated levels of acidity, often denoted by a pH value below 4.

Implementing a flap gate in the channel network alters the direction of water flow to a unidirectional flow. Fig. 7 displays the outcomes of water quality simulations conducted in a one-way flow model. The one-way flow system has the potential to distribute the flow evenly and decrease acidity levels. All the examined sites exhibit a pH level of more than 4.5 during high and low tide. The variation in water quality exhibits a relatively little discrepancy compared to the bidirectional flow.

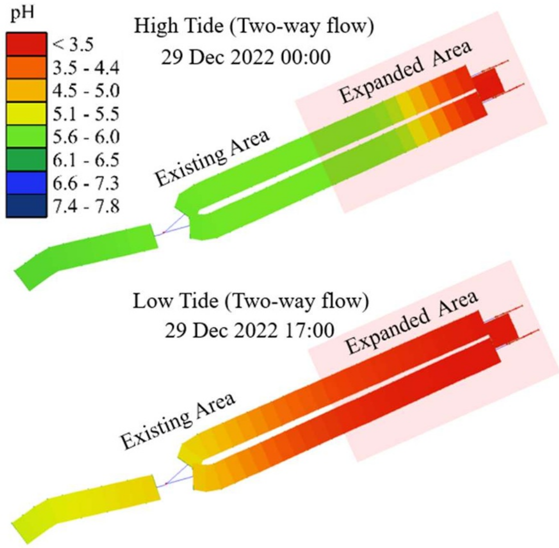

Fig. 6 The spatial distribution of pH resulting from the two-way flow simulation.

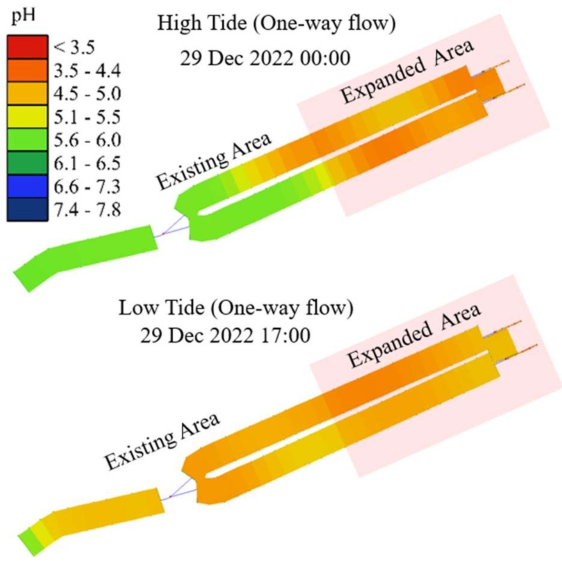

Fig. 7 The spatial distribution of pH resulting from the two-way flow simulation.

In order to conduct a more comprehensive analysis of the disparities in simulation results between one-way flow and two-way flow, the fluctuations in discharge and pH levels at three specific locations (Fig. 5), denoted as A, B, and C, were examined. The discharge and pH changes at points A, B, and C are depicted in Fig. 8, Fig. 9, and Fig.

10, respectively. At point A, which is still relatively close to the river, fluctuations in discharge due to tidal influence are visible, especially in two-way flow. In the context of one-way flow, fluctuations can be reduced, resulting in a steady flow over an extended duration. Nonetheless, the water quality remains fairly comparable between two-way and one-way flow situations (Fig. 8).

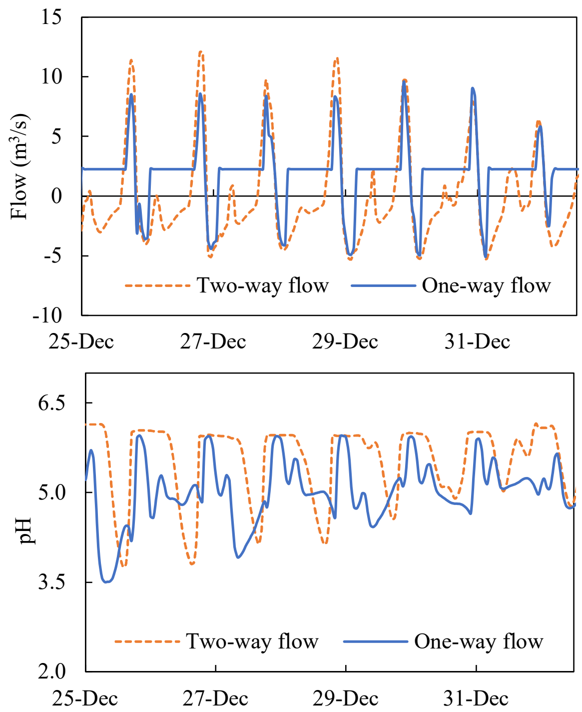

Fig. 8 Comparison between two-way and one-way simulation results at point A in terms of flow discharge and pH

The difference between two-way and one-way flow begins to become obvious at point B, which is 6.8 km from the Katingan River (Fig. 9). It is evident that the discharge flowing through this point becomes more steady when the flow is unidirectional. Fresh water from rivers can be retained as much as possible, leading to an increase in pH levels. The pH value at point B with one-way flow is higher than that with one-way flow for most of the simulation period.

Point C is located at a distance of 8.3 kilometers, which is the farthest from the Katingan River. The difference between two-way and one-way flow is most visible at this point. In a two-way system, the flow rate is negligible, resulting in the water maintaining a very acidic state with a pH level of around 3.5 (Fig. 10). In the context of the simulated one-way flow system, a significant volume of freshwater passes this particular site, resulting in an elevation in pH levels. In some cases, the pH level may exceed 5.

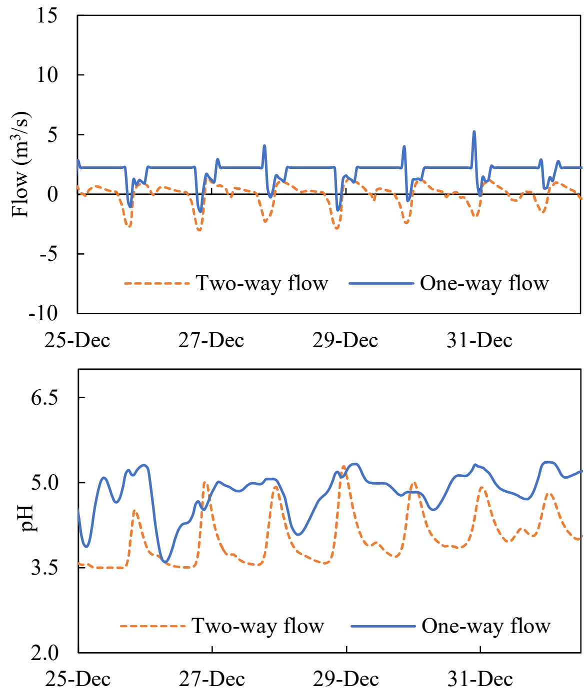

Fig. 99 Comparison between two-way and one-way simulation results at point B in terms of flow discharge and pH

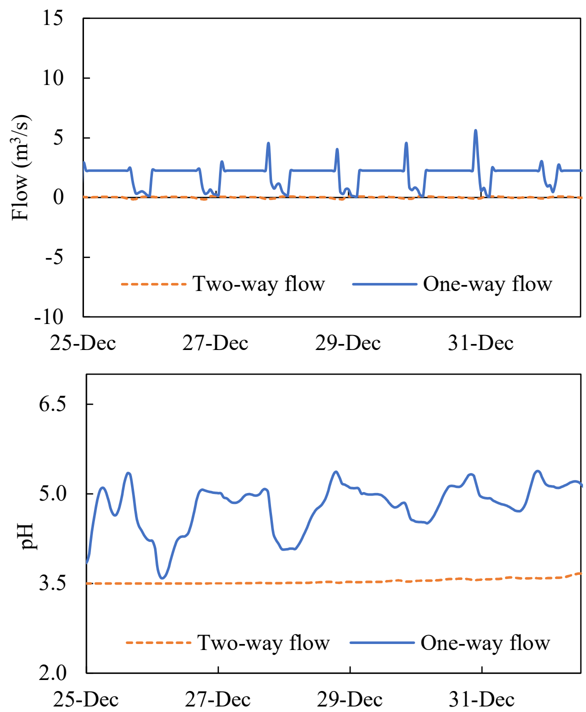

Fig. 1010 Comparison between two-way and one-way simulation results at point C in terms of flow discharge and pH

3.2 Discussion

Comparison of the effectiveness of the acid-sulphate soil leaching process in one-way and two-way flow simulations revealed significant differences. The two-way flow system in the simulation shows that fresh water from the Katingan River that enters at high tide cannot reach the end of the primary channel, even at the highest tide. There is almost no flow at the furthest point because the flow has reversed direction before the freshwater reaches the furthest location.

Although high tide positively influences water quality, the impact is only seen over a limited distance. During low tide, pH values significantly drop because there are no facilities to retain fresh water in the channel network. Increases in acidity indicate that the two-way water flow system is ineffective in distributing fresh water throughout the network and cannot flush acid effectively. Thus, locations far from rivers always show high acidity levels and an increase in acidity at low tide always occurs throughout the network.

Installing flap gates can change a two-way flow system to one-way. Setting the flap gates to allow only positive flow results in a more controlled water flow distribution, although still a small amount of reverse flow occurs. In a one-way flow simulation, water flows in a directed and consistent direction. The flow of fresh water from rivers can reach the furthest points and help improve water quality by reducing acidity in those locations. The presence of flap gates helps fresh water from rivers stay longer in the irrigation network. Therefore, a higher pH can be maintained longer during low tide, and there is no drastic drop in pH. One-way flow can flush acid water from peat and acid sulphate soil better than two-way flow.

A one-way flow system allows a more controlled and even distribution of freshwater along the network. In addition to raising the pH level, the water flow that reaches the furthest areas of the network also has a beneficial effect on fulfilling the watering requirements of crops. This discovery is consistent with previous studies conducted in Terantang, which indicate that implementing a one-way flow system has enhanced irrigation water distribution and increased water quality throughout the network [5].

The leaching and acid removal process is a process that requires much water, namely 5 cm/day [3]. The simulation results in this study show that in terms of water volume, one-way flow arrangements allow more fresh water to enter and be retained in the irrigation network than two-way flow systems. This finding is supported by previous research in Belanti [6]. Without water regulation, the volume of water in the scheme cannot carry out the acid-leaching process. By adding flap gates to regulate flow, the volume of freshwater that enters and is retained is sufficient to support the leaching and acid removal processes.

The area furthest from the river is a newly developed agricultural area. The soil in this area has a top layer of peat, which is acidic and poor in minerals. Soil with these criteria is not favorable for agricultural activities. The application of one-way flow is expected to be able to remove the peat layer more quickly, thereby accelerating soil maturation. Matured soil is good for plants and can increase agricultural production.

One-way flow systems not only provide more efficient water distribution but also have the potential to improve overall soil fertility, making a positive contribution to sustainable agricultural productivity. Thus, adopting the one-way flow principle can be an integrated solution to improve water efficiency and soil fertility, providing a solid foundation for sustainable agricultural development.

4 Conclusion

Implementing the two-way flow system in the Katingan swamp irrigation area reveals that tidal energy, which transports fresh water from the river during high tide, has not effectively improved water quality, as indicated by pH levels, throughout the primary channel. This limitation arises from the prompt return of water to the river during low tide. Consequently, the high acidity levels in the area might exert detrimental effects on agricultural activities.

One-flow implementation facilitates better and more even water circulation, guaranteeing an adequate water supply to distant service areas. Enhancing water circulation can improve water quality and accelerate the leaching process of acid-sulphate soil in agricultural areas that have undergone recent reclamation efforts. Areas located at greater distances from water sources have an opportunity to get a sufficient amount of water that is of better quality. This condition can have a favorable effect on plant growth and the possibility of increased crop yields, which can boost crop production in the region.

The findings of this study give an early overview of the significance of managing flow in tidal swamp areas with poor water quality. The appropriate option may significantly influence water quality and agriculture production, as well as provide a solid foundation for improved decision making in marsh regions like Katingan. This research, however, is currently restricted to the middle section of the irrigation network. This study may be further by creating a water management simulation model for the entire irrigation network.

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