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Variabilitas Musiman Kualitas Air dan Strategi Pengelolaan Air di Daerah Rawa Karang Agung Hilir

Seasonal Variability of Water Quality and Water Management Strategies in Karang Agung Hilir Swampland

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Abstract

To increase food production in the Karang Agung Hilir Swampland requires effective water management by understanding the hydrodynamics of water quantity and quality; however, related research remains limited. This study aims to examine the characteristics of the Karang Agung Hilir Swampland in relation to tidal variability and water quality. The method used is correlation analysis with the variables of tidal hydrodynamics, land elevation, pH, electrical conductivity (EC), and salinity in the rainy and dry seasons. Tidal influence is significant at the channel estuary but decreases toward the channel's end. The land in the middle of the navigation channel is classified as hydro-topography A (<+2.00 m), B (+2.00 m to +2.30 m), and C (>+2.30 m). During the rainy season, the pH in the estuary and mid-channel is higher during spring tide than during neap tide, influenced by elevated EC values indicating saltwater intrusion during high tides. At the channel's end, extremely acidic pH (<4.00) and EC values exceeding 2,000 µS/cm suggest the presence of an oxidized pyrite layer. In the dry season, pH levels in the channel are higher compared to the rainy season due to increased salt concentrations. Water management strategies are needed to enhance acid leaching, prevent pyrite oxidation, and limit saltwater intrusion. A one-way water management system is recommended to improve water circulation and supply, while maintaining water levels above the pyrite layer. This research is expected to provide recommendations for water management in swamplands with similar characteristics to this research location.

Keywords: *Swampland, tides, pH, salinity, hydro-topography*

Abstrak

Untuk meningkatkan produksi pangan di Daerah Irigasi Rawa Karang Agung Hilir membutuhkan pengelolaan tata air yang efektif dengan memahami hidrodinamika kuantitas dan kualitas air. namun penelitian terkait masih terbatas. Penelitian ini bertujuan mengkaji karakteristik lahan rawa Karang Agung Hilir berdasarkan variabilitas pasang surut dan kualitas air. Metode yang digunakan adalah analisis korelasi dengan variabel hidrodinamika pasang surut, elevasi lahan, pH, konduktivitas listrik (EC), dan salinitas pada musim hujan dan kemarau. . Pengaruh pasang surut tinggi terjadi di muara saluran, namun berkurang di bagian hilir saluran. Lahan di bagian tengah saluran navigasi diklasifikasikan menjadi hidrotopografi A (<+2.00 m), B (+2.00 m s/d +2.30 m), dan C (>+2.30 m). Pada musim hujan, pH di muara dan tengah saluran lebih tinggi saat spring tide dibandingkan neap tide, dipengaruhi oleh nilai EC yang menunjukkan keberadaan kandungan garam dari air pasang. Pada ujung saluran, kualitas air menunjukkan keasaman ekstrem (pH <4.00) dan nilai EC >2.000 µS/cm, yang mengindikasikan keberadaan lapisan pirit teroksidasi. Pada musim kemarau, pH air di saluran lebih tinggi dibandingkan musim hujan karena tingginya kandungan garam. Pengelolaan tata air diperlukan untuk mempercepat pencucian zat asam, mencegah oksidasi pirit dan intrusi air asin, melalui penerapan sistem tata air satu arah yang dapat meningkatkan sirkulasi serta suplai air, dan menjaga muka air tetap berada di atas lapisan pirit. Penelitian ini diharapkan dapat menjadi rekomendas pengelolaan tata air pada lahan rawa dengan karakteristik yang sama dengan lokasi penelitian ini.

Kata Kunci*: Rawa, pasang surut, pH, salinitas, hidrotopografi*

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INTRODUCTION

The development of swamplands in Indonesia aims to meet national food demands (Irmawati et al., 2015). Historically, local communities in coastal Kalimantan began in the 18th century to construct channels connecting two rivers (known as the anjir system) as a water source for reclaiming land into agricultural areas (Sulaiman et al., 2019). However, converting swamplands into productive agricultural land faces challenges such as flooding during the rainy season, drought in the dry season, and the presence of pyrite, which can inhibit crop growth. Additionally, a lack of available farmers poses a challenge, as most swamplands are situated in remote regions.

Swampland development holds significant economic potential when supported by proper water and land management, as demonstrated in Mampai Village, Central Kalimantan (Sunaryati & Wahib Muhaimin, 2022), and Braja Selebah District, East Lampung Regency (Berliana et al., 2021). Effective water management is a key factor in the success of swampland development. The regulation of water supply and drainage through sluice gates (Zevri et al., 2023), along with supporting infrastructure and farmer participation, directly influences agricultural productivity (Hairani & Noor, 2021). Agronomic and social factors are equally important, including fertilization, rice varieties, planting systems, pest control, and post-harvest handling, along with the integration of technological innovations. On the social side, enhancing farmer involvement in network operation and maintenance, as well as promoting independent water management funding, is essential (Firdha Tafarini & Yazid, 2018; H.S. & Noor, 2019; Masulili, 2015; Purba & Yazid, 2018; Sulaiman et al., 2019; Zahra et al., 2024). The local farmers' knowledge in cultivating food crops also plays a critical role in the successful development of swampland (Ratmini & Herwenita, 2021).

Water management systems in swamplands require improvements in both infrastructure and monitoring technologies. In tidal swamplands, water control structures are essential to regulate water levels, prevent over-drainage, and accelerate leaching and soil maturation (Pramono et al., 2021; Pranata et al., 2024). Monitoring both water quantity and quality is necessary to understand the hydrological dynamics and characteristics of swamplands. Spatial and temporal water quality measurements serve as a foundation for effective water management, especially in areas with acid-sulfate soils (Multazam et al., 2022). In recent years, swamplands in Indonesia have employed Real-Time Telemetry (RTT) systems to monitor water quality and quantity, including locations such as Dadahup (Zevri, 2023), Katingan (Kamil et al., 2024) in Central Kalimantan, and Karang Agung Hilir in South Sumatra (BBWS Sumatera VIII, 2023).

Swamplands are categorized as suboptimal or marginal lands(Badan Penelitian dan Pengembangan Pertanian, 2014), characterized by low nutrient availability, vulnerability to degradation (Susilawati et al., 2017), and the presence of a pyrite layer. Peatlands may contribute to increased canal water acidity (Hadi et al., 2024a), and hydro-topography variations affect the spatial distribution of pH and salinity. To prevent pyrite oxidation, water levels must be maintained above the pyrite layer. This can be achieved by operating water control gates and widening channels (Fauzan et al., 2021; Ngo Dang et al., 2010), as well as through soil treatment methods such as mulching, the construction of bunds, and ploughing to reduce evapotranspiration and soil desiccation (Minh et al., 1998).

Effective water management is needed to increase rice production in swamplands by understanding the hydrodynamics of water flow, water quality, mapping of land and water systems (Susilawati et al., 2017). Tidal swamplands are influenced by factors such as water level, land elevation, pyrite depth, peat layers, water quality, and soil condition. Similarly, development in lebak swamplands must adapt to their specific land classification (Herwenita & Hutapea, 2018). To date, studies on swampland characteristics have been limited to a few regions in Indonesia, including food estate areas in Central Kalimantan and Merauke, Papua. Therefore, this study aims to identify the characteristics of the Karang Agung Hilir swampland, based on seasonal tidal dynamics and water quality, in order to provide recommendations in water management so as to increase food production and is expected to be applied to swamplands with similar characteristics.

METHODOLOGY

Research Location

South Sumatra Province contains approximately 326,041 hectares of swampland. **Figure 1** illustrates the spatial distribution of swamp irrigation networks, extending from the northeastern border near the Bangka Strait to the southwestern region. In Indonesia, the authority for managing lowland irrigation areas is classified into three categories based on area size: Central Government, Provincial Government, and Regency/Municipal Government. In South Sumatra, lowland irrigation areas under the Central Government's authority cover 22 Daerah Irigasi

Rawa (DIRs) totaling 237,133 ha. The Provincial Government manages 27 DIRs covering 49,509 ha, while District Governments oversee 7 DIRs totaling 39,399 ha (Permen PUPR No. 14 Tahun 2015 2015).

The Karang Agung Hilir swampland is located at 2°16'27.12" S and 104°40'7.38" E, spanning across Banyuasin and Musi Banyuasin Regencies with a total area of 16,127 ha (Permen PUPR No. 14 Tahun 2015). Situated 18 km inland from the coastline, the area derives its primary water source from the Lalan River, which discharges into the Bangka Strait (**Figure 1**).

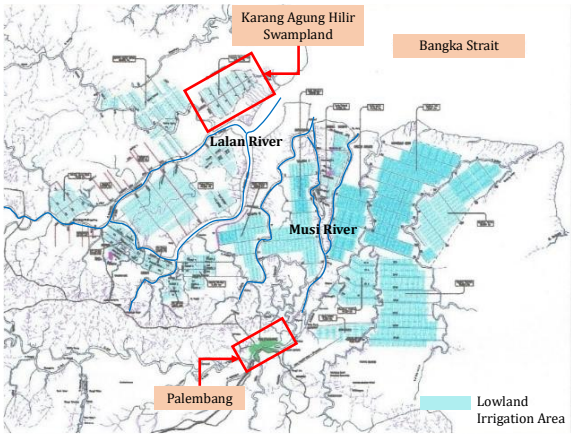

Figure 1 Distribution of Lowland Area in South Sumatra (*BBWS Sumatera VIII, Ministry of Public Works and Housing, 2011*)

Reclamation of the Karang Agung Hilir area was initiated during the 1970s–1980s through the P4S-IPB and Nedeco-Euroconsult programs (Koswara & Rumawas, 1984). The current water system has evolved into a semi-controlled to fully controlled management system (Suryadi, 1996), characterized by:

- Sluice gates installed in secondary channels to regulate tidal inflow and outflow
- Active farmer organizations
- Adoption of high-yield rice varieties
- Integration of real-time telemetry systems for water quality monitoring

The canal system follows a "comb" configuration, comprising navigation, primary, sub-primary, secondary, and tertiary channels. As illustrated in **Figure 2**, during high tide, water flows from the primary to the secondary channels through flap gates. Conversely, during low tide, water drains back from the secondary to the collector and sub-primary channels, forming a unidirectional flow system.

The region is dominated by acid sulfate soils, with pH ranging from 3.50 to 5.45, and contains shallow pyrite layers along with peat deposits of 50–100 cm thickness (Syahfitri, 2021). Exposure of the pyrite layer, particularly in the dry season, leads to oxidation. Through capillary rise, Al^{3+} ions migrate to the topsoil, increasing soil and water acidity. To mitigate this, it is essential to maintain the water table at approximately 30 cm depth to prevent drying and oxidation (Minh et al., 1998).

Figure 2 Flow Conditions during high and low tide

Data and Method

Recent technological advances have enabled real-time water management in agricultural areas through the integration of sensors, internet connectivity, and centralized data systems (Ramirez et al., 2022; Suhaimi et al., 2021; Zevri, 2023). This allows for faster and more practical monitoring of water quality and quantity, offering higher efficiency compared to manual tools such as water level gauges and portable pH and EC sensors.

During 2022-2023, BBWS Sumatera VIII has installed eight Real-Time Telemetry (RTT) units in the Karang Agung Hilir swampland. These sensors measure water level, pH, and electrical conductivity (EC). In this study, data were collected from RTT units 1 (estuary), 4 (middle), and 7 (end) of the primary channels, as shown in **Figure 3**. The water level, pH, and EC sensors are connected to a data logger housed in the telemetry station, as shown in **Figure 4**. Recorded data are transmitted via the internet and can be accessed directly through an online platform.

Figure 3 Swamp Irrigation Network System and Real-Time Telemetry Locations (*Google Earth Pro, 2024*)

Figure 4 Real Time Telemetry (RTT)

Water level, pH, and EC data were collected at hourly intervals over 14-day periods, both in the rainy season (1–14 January 2024) and the dry season (10–24 July 2024). Measurements were conducted in the primary channel, which lacks water control structures, unlike the secondary channel, which is equipped with flap gates. At the upstream section of the secondary channel, water can enter during high tide but is blocked during low tide, causing water to exit via the downstream section into sub-primary and collector channels.

Water level data from the rainy and dry seasons were analyzed to determine hydro-topography elevation. Hydro-topography categories were determined based on the classification system presented in **Figure 5**.

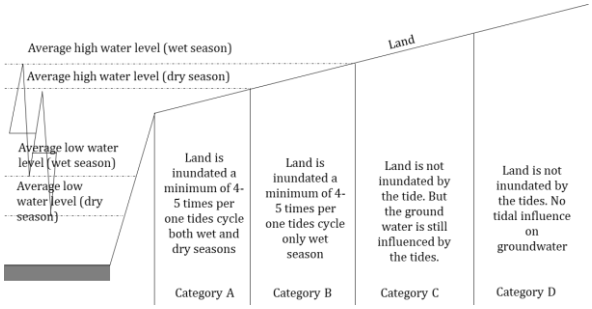

Figure 5 Hydro-topography categories in Tidal Swampland (Suryadi, 1996)

In hydro-topography A, the land is inundated by tidal water 4–5 times per cycle, both in the rainy and dry seasons. Land classified as hydro-topography B is inundated 4–5 times per cycle but only during the rainy season. Hydro-topography C land is not directly inundated, although the groundwater table is still affected by tidal fluctuations. Hydro-topography D land is not affected by tides at all (Suryadi, 1996). The collected pH and EC data were analyzed based on location and seasonal variation to characterize the Karang Agung Hilir swampland, assess its seasonal dynamics, and develop appropriate zoning for swamp management.

RESULT AND DISCUSSION

Hydro-topography

The Karang Agung Hilir Swampland lies at an elevation ranging from +1.50 m to +2.50 m, as shown in **Figure 6**. In the northwestern region, the elevation reaches up to +2.50 m, while the southern and southeastern regions are lower, ranging from +1.50 to +2.00 m. During the rainy season, the highest water level elevation at Location 4 (the middle of the navigation channel) was +2.28 m, which is lower than the water level recorded at Location 1 (the estuary), which reached +3.42 m. This observation indicates that tidal energy diminishes progressively along the channel due to frictional and structural resistance. As a result, at the downstream end of the navigation channel, the maximum water level was only +1.92 m.

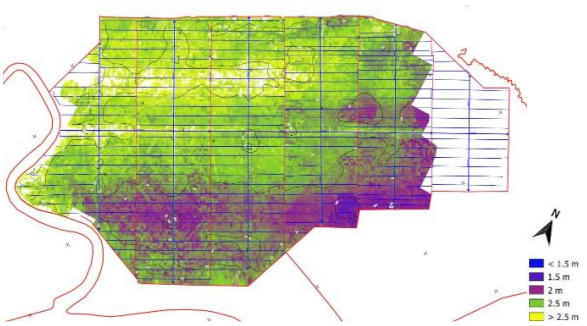

Figure 6 Elevation Map of Karang Agung Hilir Swampland

Figure 7, shows seasonal variations in water level at Location 4, which represents the central section of the system and is the primary conduit of Karang Agung Hilir's tidal flow. By comparing water level data with the surrounding land elevation, hydro-topography classification was established based on Suryadi (1996):

- Hydro-topography A: land elevation < +2.00 m (inundated 4–5 times per tidal cycle, year-round)
- Hydro-topography B: land elevation +2.00 m to +2.30 m (inundated only during rainy season tidal peaks)
- Hydro-topography C: land elevation > +2.30 m (not inundated; only shallow groundwater affected by tides)

The hydro-topography analysis in this study is limited to the vicinity of Location 4, where continuous water level data were collected. Consequently, the hydro-topography zoning presented only applies to the middle section of the navigation channel. For a more detailed and spatially comprehensive classification, future research should implement hydrodynamic modeling or GIS-based spatial simulation to delineate micro-zones of hydro-topography across the entire swampland. Given the significant reduction of tidal amplitude from the estuary to the inner sections of the channel, the influence of tidal energy loss must be considered in zoning and water management planning.

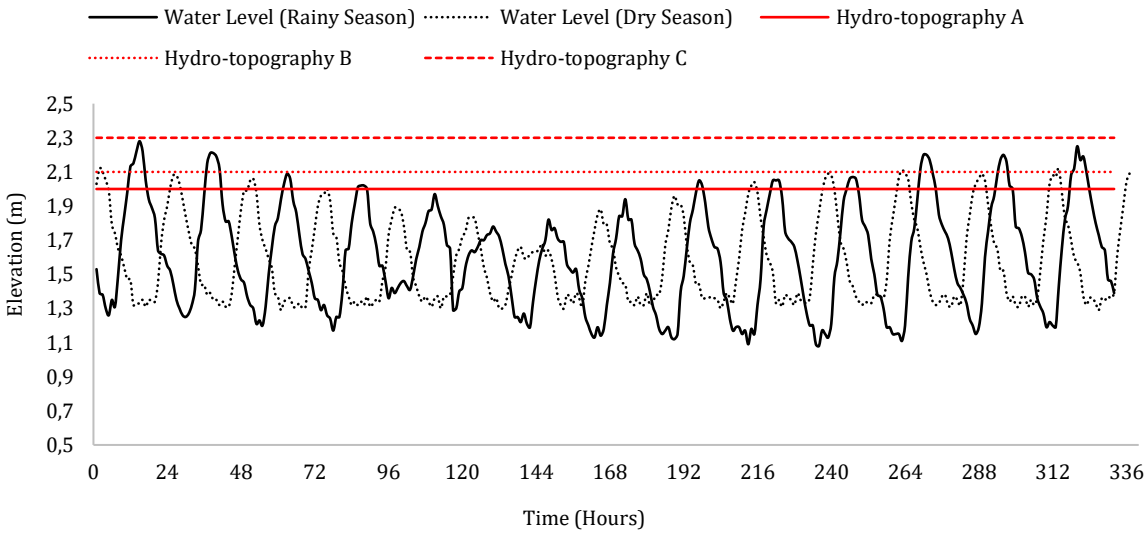

Figure 7 Hydro-topography Classification in the Middle Section of the Karang Agung Hilir Navigation Channel

Water Quality in Rainy Season

Real-time telemetry (RTT) data were collected from January 1 to 14, 2024. **Figure 8** shows that at the estuary of the navigation channel, water pH during spring tide ranged from 3.56 to 5.87, which is higher than during neap tide (3.11–4.05). Electrical conductivity (EC) during spring tide ranged from 5 to 4495 µS/cm, and during neap tide, from 2 to 3000 µS/cm, indicating that tidal activity contributes to salinity variations and thus influences water quality in the navigation channel. During the daily tidal cycle, water pH in the channel tends to rise during high tide and decline during low tide, indicating that acid-leaching from the land remains active, with acidic substances being discharged into the channels during low tide through drainage processes.

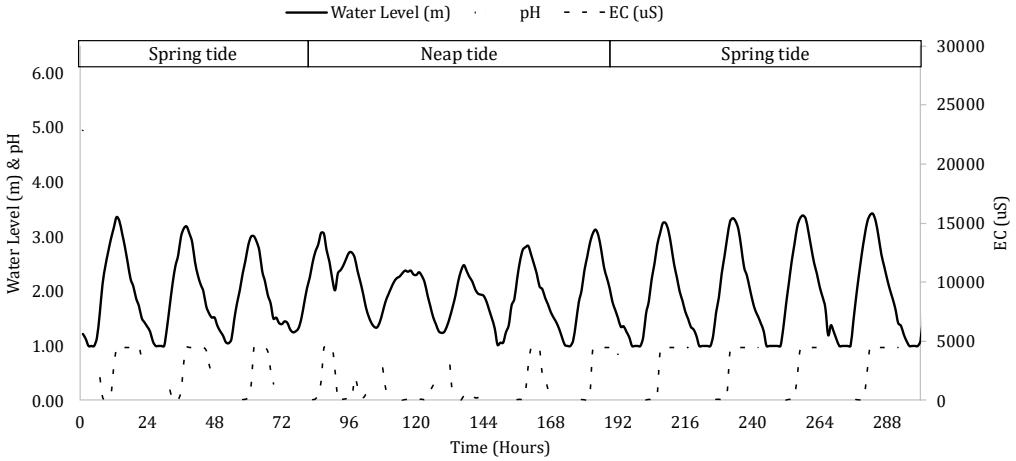

Figure 8 Water Level, pH, and EC at Location 1 (Estuary) in the Rainy Season

The high tide water level in the middle section of the navigation channel is lower than at the estuary (Lalan River). As shown in **Figure 9**, the maximum water elevation reaches +2.28 m in the middle, compared to +3.42 m at the estuary. Water pH in the middle of the channel ranges from 4.71 to 5.34 during spring tide, and from 2.47 to 5.14 during neap tide. At the 107th hour during neap tide, pH dropped from 5.06 to 2.95, likely due to the flushing of acidic substances from adjacent rice fields. As illustrated in **Figure 9**, the simultaneous decrease in pH and increase in EC at that hour suggest that acid leaching from rice fields occurs during the rainy season, with acidic compounds being transported through secondary and subprimary channels, lowering the pH of channel water. EC values show no significant difference between spring tide (1.929–2.187 µS/cm) and neap tide (1.958–2.292 µS/cm).

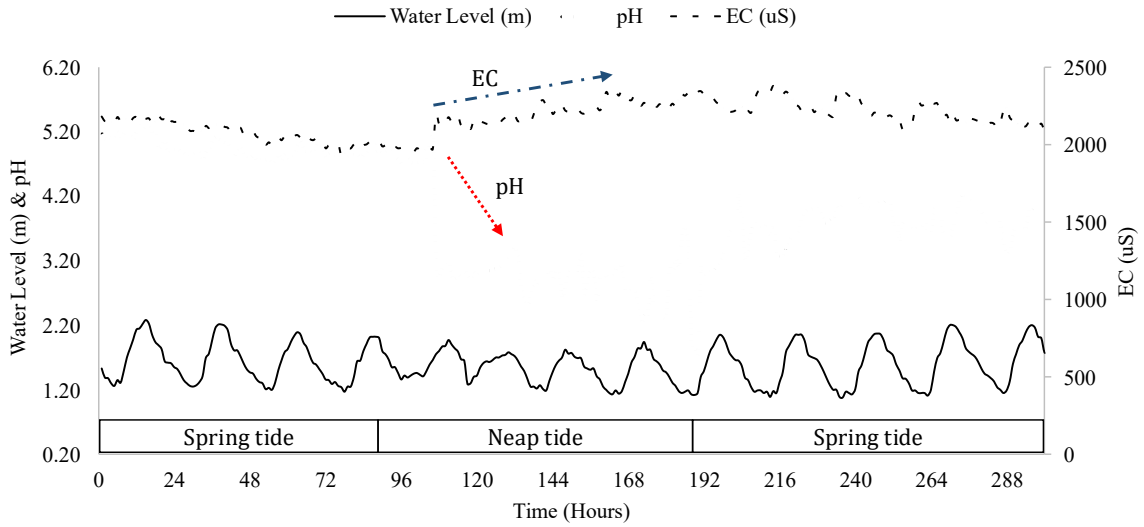

Figure 9 Water Level, pH, and EC at Location 4 (Middle) in the Rainy Season

At the downstream end of the navigation channel, tidal influence remains evident, with the highest water level reaching +1.92 m—lower than at the estuary and middle sections of the channel **Figure 10** . There is no significant difference in pH between spring tide (3.26–3.87) and neap tide (3.23–3.49), with both falling into the very acidic category (Schoeneberger et al., 2012). EC values during spring tide range from 3.152 to 4.637 µS/cm and during neap tide from 2.962 to 3.536 µS/cm, categorized as high. A notable decline in EC occurred between hour 264 and 336, from approximately 3.500 µS/cm to 2.000 µS/cm, possibly due to rainfall events that flushed acidic substances from the soil, reducing conductivity levels. However, the lack of rainfall data at the study site limits the analysis to pH, EC, and water level measurements; acquiring such data is recommended for future studies.

Water quality at the downstream end of the navigation channel differs from that at the middle and estuary, characterized by very acidic pH and high EC. This indicates that high EC levels are not caused by tidal salinity but rather by oxidized pyrite in the soil.

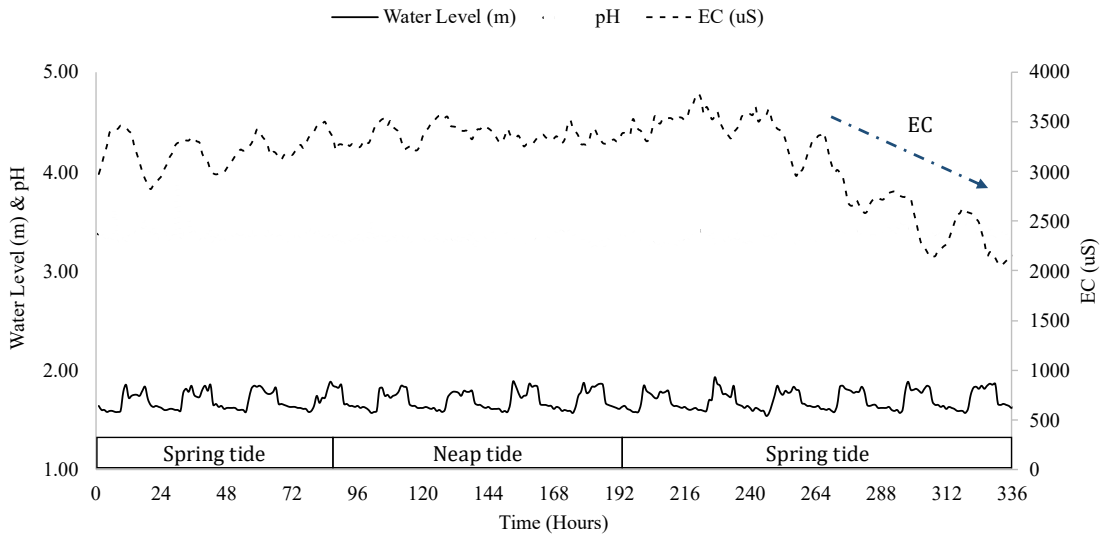

Figure 10 Water Level, pH, and EC at Location 7 (End) in the Rainy Season

As shown in **Table 1** and **Figure 11**, water pH in the estuary and middle of the navigation channel is higher during spring tide compared to neap tide. In contrast, at the downstream end of the channel, the pH shows little variation between spring and neap tides and remains in the very acidic category

(pH < 4.00). This suggests that flow length significantly influences water quality degradation from the estuary toward the channel's end. At the estuary, EC values are higher during spring tide than during neap tide, whereas in the middle of the channel, EC variation between the two tidal conditions is not significant. At the downstream end of the navigation channel, EC values during neap tide ranged from 3,213 to 3,558 µS/cm, and even during daily low tides, EC values remained above 2,000 µS/cm. This indicates that the elevated EC is not primarily due to salinity intrusion from tides, but rather from oxidized pyrite in the soil, which generates acidity and is mobilized during low tide conditions.

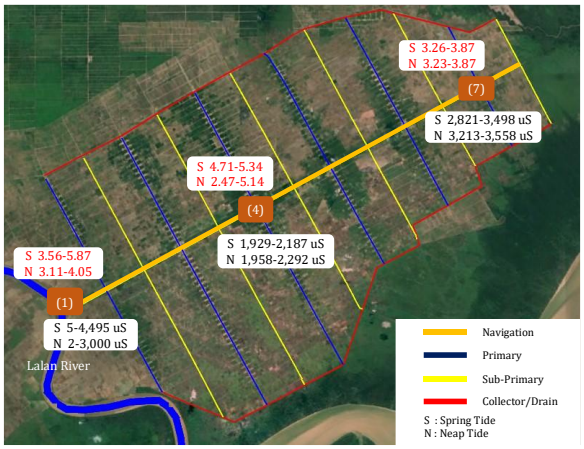

Figure 11 Distribution of pH and EC during the rainy season

Table 1 Comparison of pH and EC during the rainy season in navigation channels

Location	pH (Spring Tide)	pH (Neap Tide)	EC (µS/cm, Spring Tide)	EC (µS/cm, Neap Tide)
(1) Estuary	3.56 - 5.87	3.11 - 4.05	5.00 - 4,495.00	2.00 - 3,000.00
(4) Middle	4.71 - 5.34	2.47 - 5.14	1,929.00 - 2,187.00	1,958.00 - 2,292.00
(7) End	3.26 - 3.87	3.23 - 3.49	2,821.00 - 3,498.00	3,213.00 - 3,558.00

Water Quality in Dry Season

During the dry season, the water pH at the estuary ranges from 5.54 to 7.40 during spring tide and from 6.43 to 7.03 during neap tide, as shown in **Figure 12**. Electrical conductivity (EC) values range from 3,172 to 5,718 µS/cm during spring tide and from 1,122 to 3,854 µS/cm during neap tide. At spring tide, the EC value peaks at 5,718 µS/cm during high tide and gradually decreases to 2,444 µS/cm at neap tide. This reduction is attributed to the decreased salt content in tidal inflow during neap tide, which correlates with lower EC value (Taylor, 1991).

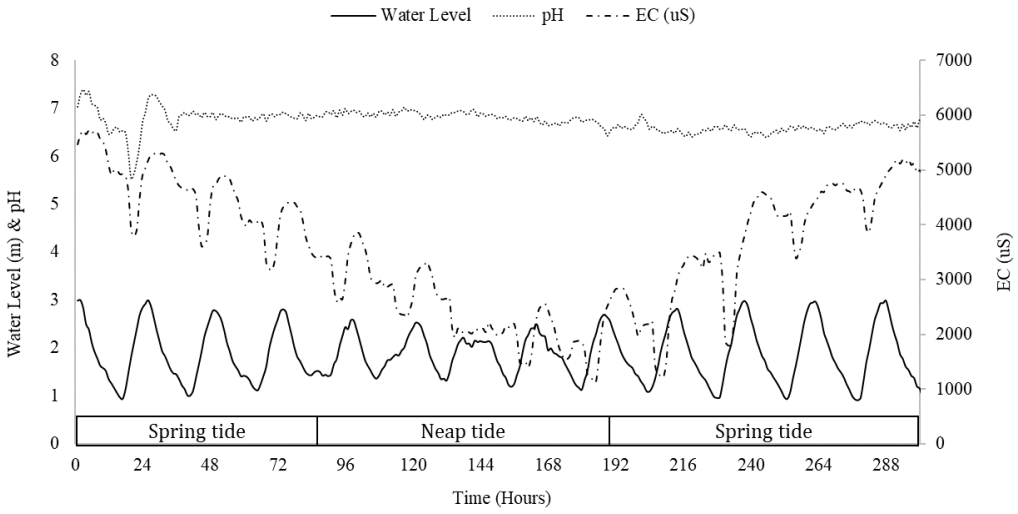

Figure 12 Water Level, pH, and EC at Location 1 (Estuary) in the Dry Season

The increase in pH is associated with the salt content transported by high tides. EC values can be converted into salinity, with 1,000 µS/cm equivalent to 1 dS/m; thus, salinity at the estuary ranges from 3.17 to 5.72 dS/m during spring tide and 1.12 to 3.85 dS/m during neap tide. Based on salinity classification, land suitability for tidal swamp rice cultivation in the dry season falls into the S2 category (salinity 4–6 dS/m), which is moderately suitable but may present limitations that can be managed by local farmer (Wahyunto et al., 2016).

In the middle section of the channel, pH ranges from 4.93 to 5.95 and EC from 1,043 to 3,866 µS/cm during spring tide. During neap tide, pH ranges from 4.63 to 5.65 and EC from 427 to 3,707 µS/cm, as illustrated in **Figure 13**. Water pH in the channel's middle section tends to increase with rising EC, indicating continued influence from saline tidal inflow. At hour 162, corresponding to the second spring tide cycle, a significant EC fluctuation was observed due to tidal influence transporting salt content inland; thus, EC patterns follow the daily tidal rhythm. Salinity levels are lower than those at the estuary, ranging from 1.04 to 3.71 dS/m, classifying the area within the S1 category (highly suitable) for rice cultivation.

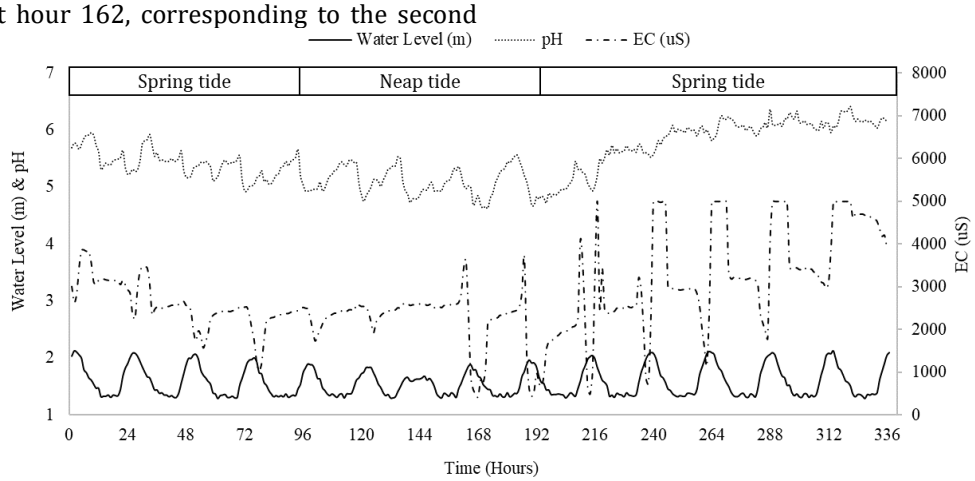

Figure 13 Water Level, pH, and EC at Location 4 (Middle) in the Dry Season

During the dry season, at spring tide, pH ranges from 5.34 to 6.07 and EC from 962 to 2,935 µS/cm; at neap tide, pH ranges from 5.30 to 6.50 and EC from 2,093 to 2,996 µS/cm (**Figure 14**). Elevated pH and EC values suggest that tidal influence carrying salt content still affects the end of the channel, unlike during the rainy season, when low pH and high EC are attributed to oxidation of the pyrite layer. Salinity values range from 0.96 to 3.00 dS/m, indicating a land suitability classification of S1 (highly suitable). Tidal activity may raise pH at the end of the navigation channel during the dry season; however, water level elevation and pyrite layer depth must be considered. Oxidation of shallow pyrite layers can occur if the water table drops too low. At the channel's end, water levels range from +1.34 m to +1.98 m, while land elevation exceeds +2.00 m. Therefore, precautionary measures such as regulating water gates and utilizing pumps are necessary to prevent pyrite oxidation.

Significant EC fluctuations are observed at the end of the second spring tide period, corresponding with the tidal cycle. EC increases during high tide due to salt content transported by tidal inflow. Toward the end of the second spring tide period, a slight increase in pH suggests possible rainfall, contributing to the observed EC fluctuations

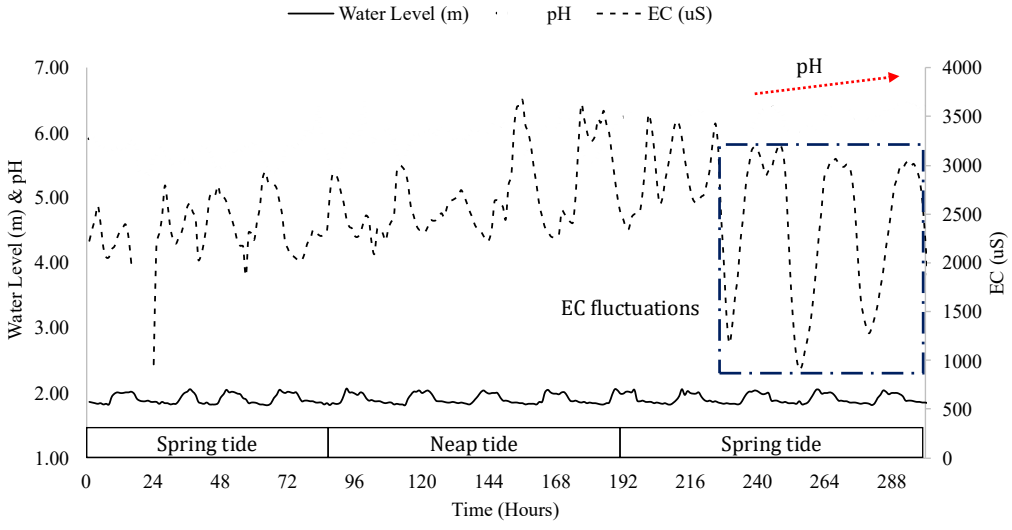

Figure 14 Water Level, pH, and EC at Location 7 (End) in the Dry Season

During the rainy season, a significant difference in pH is observed between spring tide and neap tide; conversely, no substantial difference is evident during the dry season (**Table 2** and **Figure 15**). This is attributed to rainfall and increased freshwater discharge from the upstream Lalan River during the rainy season, which reduces the tidal influence compared to the dry season.

In the rainy season, pH in the middle of the navigation channel ranges from 1.75 to 5.34, indicating extreme acidity, whereas in the dry season, it ranges from 4.18 to 6.41, indicating strong acidity (Schoeneberger et al., 2012). Since pH is influenced by salt content transported during high tides, it tends to be higher in the dry season than in the rainy season (**Figure 16**). EC values fluctuate daily in the dry season due to tidal cycles, whereas in the rainy season, EC remains relatively stable (**Figure 17**). Based on land suitability criteria (**Table 3)**, pH values correspond to an S2 classification (moderately suitable) during both rainy and dry seasons. In contrast, salinity levels indicate S1 classification (highly suitable) for land use during both seasons.

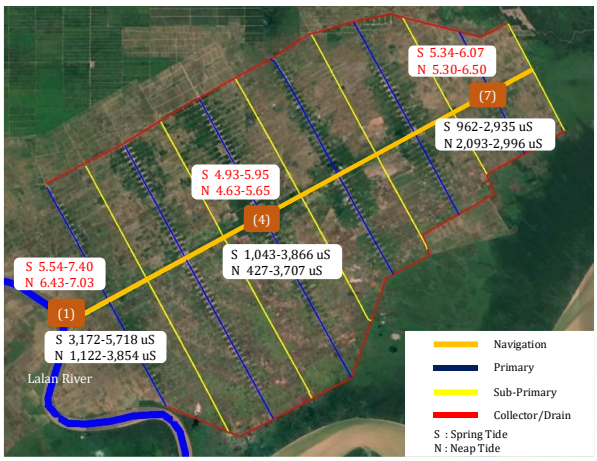

Figure 15 Distribution of pH and EC in Dry Season

Table 2 Comparison of pH and EC during the dry season in Navigation Channels

Location	pH (Spring Tide)	pH (Neap Tide)	EC (µS/cm, Spring Tide)	EC (µS/cm, Neap Tide)
(1) Estuary	5.54 - 7.40	6.43 - 7.03	3,172.00 - 5,718.00	1,122.00 - 3,854.00
(4) Middle	4.93 - 5.95	4.63 - 5.65	1,043.00 - 3,866.00	427.00 - 3,707.00
(7) End	5.34 - 6.07	5.30 - 6.50	962.00 - 2,935.00	2,093.00 - 2,996.00

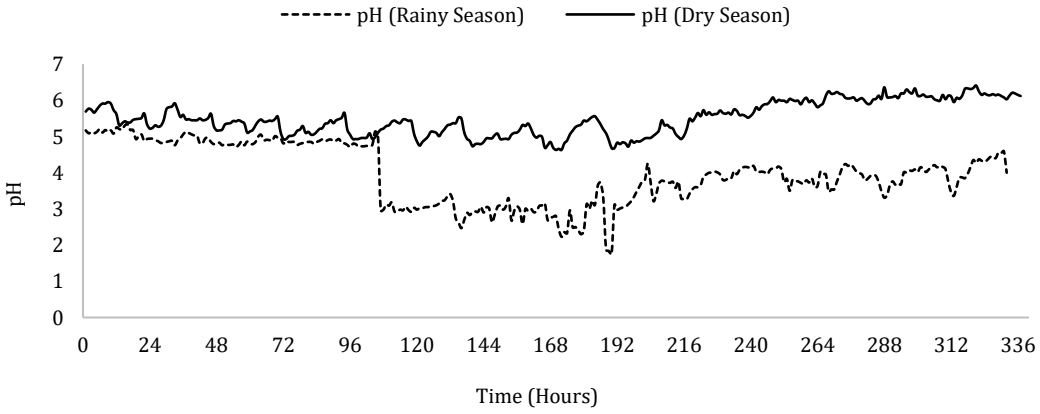

Figure 16 Comparison of pH in the middle of the navigation channels

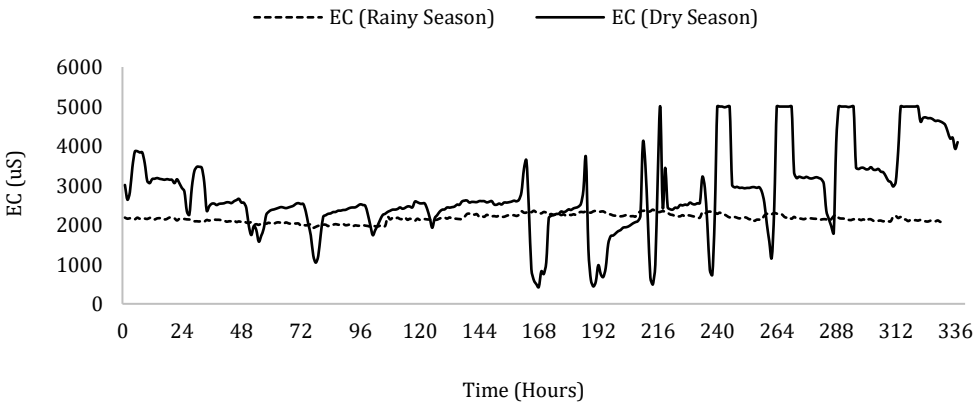

Figure 17 Comparison of Electrical Conductivity (EC) in the middle of the navigation channel

Table 3 Land use requirements for water salinity and pH values in tidal swamp rice crops (Wahyunto et al., 2016)

Requirements	S1	S2	S3	N
Salinity (ds/m)	<4	4-6	6-8	>8
pH	5.5-7.0	5.0-5.5	<5.0	-
		7.0-8.0	>8.0	

Recommendations for Water and Land Management Strategies

During the rainy season, water quality at the end of the navigation channel is very acidic (pH <4.00) with EC>2,000 µS/cm, indicating the presence of oxidized pyrite; therefore, water regulation is required to raise the water level. Land with hydro-topography classes B and C is more vulnerable to pyrite oxidation because the water table is lower than land elevation. To improve water circulation at the end of the navigation channel, operation of the gates and pumps is required. The ga should be opened during high tides to raise the water level and closed during low tides to maintain the water table above the pyrite layer.

Pumps are only used on non-inundated land in the rainy season, where tidal energy is insufficient to reach the channel's end, making water level augmentation in rice fields necessary. The combination of gates and pumps enables inundation of rice fields in high hydro-topography areas (B and C), resulting in a water level higher than the pyrite layer. Sufficient and appropriate water circulation in the rice field can increase the leaching and flushing process, thereby increasing the pH and decrease EC caused by pyrite oxidation.

During the dry season, water levels in the navigation channel are lower than in the rainy season, but salinity is higher. Pyrite becomes more susceptible to oxidation with lower water tables and salt-laden tides. Therefore, innovations in water system design and alternative cropping systems are necessary during the dry season. Water management must overcome drought, extreme pH and salinity, by adding freshwater from the estuary by pushing water using a pump from the primary to the secondary channel and then discharging it into the collector channel at low tide, thus the water flow becomes one-way, where fresh water is not mixed with water from rice field containing acid substances. The role of gates is significant to separate the high and low tide water flows. This method is more effective for water circulation and delivery to land located farther from the source (Hadi et al., 2024b) and has been shown to reduce Fe concentration by half compared to a two-way system (Riduan et al., 2022) Alternatively, planting secondary crops such as corn is recommended to maintain land productivity during the dry season.

CONCLUSIONS

Effective planning, the application of appropriate technologies, and active farmer participation are essential for large-scale and sustainable swampland development. Spatial and temporal mapping of swamplands, particularly in tidal areas, is crucial to inform integrated water management strategies. Understanding the dynamics of both water quantity and quality is key to determining suitable management systems. The tidal influence at the estuary of the Karang Agung Hilir navigation channel is pronounced, yet diminishes significantly toward the channel's end. Land along the middle section of the navigation channel is characterized by hydro-topography A (elevation < +2.00 m), hydro-topography B (+2.00 m to +2.30 m), and hydro-topography C (> +2.30 m). These variations strongly influence the potential for pyrite oxidation and subsequent soil acidity.

During the rainy season, pH levels in the estuary and middle sections of the channel are higher at spring tide than at neap tide. EC values at the estuary are also higher during spring tide. However, in the middle channel, EC values show no significant difference between tidal phases, suggesting limited tidal influence on salt transport in that area. At the end of the channel, water remains highly acidic (pH < 4.00) and EC exceeds 2,000 µS/cm during both tidal phases, indicating minimal influence of tides and a dominant role of pyrite oxidation.

In the dry season, both pH and EC values are higher than in the rainy season, driven by increased tidal salinity and reduced freshwater input from the upstream Lalan River. Based on pH, land suitability falls under class S2 (moderately suitable), while based on salinity, it remains in class S1 (suitable) for tidal swamp rice cultivation.

To prevent pyrite oxidation, appropriate water management is critical, particularly on lands with hydro-topography classes B and C, where water tables are typically lower than the soil surface. A one-way water system is recommended to enhance water circulation and supply. Sluice gates should be opened during high tide to increase water levels and closed during low tide to maintain water tables above the pyrite layer. Additionally, pumps can be utilized to deliver freshwater from the estuary to the end of the channel during high tide, thus improving water quality and pH conditions. Water level regulation should also aim to limit salt intrusion into rice fields, particularly in the dry season. This study is limited to the assessment of water quantity and quality in navigation channels. Future research should expand to include

measurements in primary, secondary, and tertiary irrigation channels, as well as directly within rice fields, to develop a more comprehensive understanding of water-soil-crop interactions in tidal swamp environments. Swamplands have their own uniqueness and characteristics. This research is expected to provide guidelines or recommendations for water management in swamplands with similar characteristics to this research location.

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