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IMPACT OF CLIMATE CHANGE ON INUNDATION IN THE KATINGAN TIDAL AGRICULTURAL LOWLAND, CENTRAL KALIMANTAN

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Graphical abstract

Abstract

Uncontrolled tidal overflows inundated Katingan's tidal agricultural lowland. Inundation is worsening due to the impact of climate change. This condition will decrease the productivity of paddy fields. Therefore, a study was conducted with several objectives to obtain the area, water level, and duration of inundation in paddy fields as an impact of climate change and proposed sustainable water management. The methods used are tidal measurements and hydrodynamic analysis using HEC-RAS. The highest tide was at +4.52 m, while the elevation of the paddy fields was only +3.40 m; thus, the paddy fields were inundated during the spring tide. Sea level rise and rainfall increase the area, water level, and duration of inundation. During spring tide, the inundation area is 73.42%, with a duration of inundation of 3.11 days. Under sea level rises of 25 and 50 years, the inundation area increases to 74.41% and 74.86%, while the inundation duration increases to 3.28 and 3.40 days, respectively. Under rainfall with a 5- and 25-year return period, the inundation area reaches 79.19% and 79.21%, while the duration is 3.40 and 3.48 days, respectively. Paddy fields are continuously inundated for over three days at elevations of +3.70–3.80 m. Excessive inundation during prolonged periods decreased rice production. Preventive actions due to climate change are needed to control the inundations. Inundation control can be conducted by gates, canal excavation, embankments, and drain pipes. Meanwhile, integration between government sectors and local communities is needed to support the sustainability of the Katingan tidal agricultural lowlands.

Keywords: Climate change, Hydrodynamic analysis, Increased rainfall, Decreased paddy fields, Sea level rise

1.0 INTRODUCTION

Tidal lowlands in Indonesia have long been developed into agricultural land. Traditional development has been carried out since the 1890s by the Banjar and Bugis communities. The Indonesian government was inspired by the success of local communities in reclaiming the lowlands massively. Indonesian government reclaimed lowlands through the tidal paddy field opening project in the 1970s-1980s [1]. Tidal lowlands were developed due to decreased highland paddy fields and to achieve rice self-sufficiency. In Indonesia, tidal lowland irrigation is located in Sumatra, Kalimantan, and Papua. The area of tidal lowland reached 1,286,394 ha [2] and 488,852 ha as paddy fields [3].

Katingan is one of the tidal lowland areas developed into paddy fields in Central Kalimantan Province. The water system problem in Katingan tidal lowlands is overflowing tides, causing excessive inundation, as shown in Figure 1. Inundation causes paddy fields, settlements, and infrastructure to be inundated. The lack of a water system worsens the current conditions, such as canal sedimentation, causing decreases in the canal's flow capacity [4], as seen in Figure 2. Inundation is caused by a lack of water systems at the micro and macro levels. At the macro level of the water system, land use change and massive forest degradation have increased the frequency of flooding [5].

The present hydrological disasters are triggered by climate change. In tropical and coastal areas, climate change impacts sea level rise [6] and increased rainfall [7]. The rainfall intensity increases in the wet season and decreases in the dry season [8].

Figure 1 Tidal overflow on paddy fields

Figure 2 Sedimentation on secondary canals

Sea level rise has a negative impact on coastal areas. In Pekalongan, north of Java Island, sea level rise changes in the shoreline and submerged agricultural land [9]. In a study conducted in the coastal agricultural area of Upazila, Bangladesh, sea level rise causes tidal inundation and decreased cultivable land [10]. In the Mekong and Red Rivers, Vietnam, sea level rises damaged coastal cropland and needed preventive actions to minimize the negative impacts [11][12]. Excessive water occurs in the Asian Mega Deltas of Bangladesh, Vietnam, and Myanmar due to sea level rise and extreme rainfall [13]. Climate change also increased drought seasons, decreased soil fertility, and reduced food security [14].

Sea level rise causes increasing the inundation in tidal agricultural lowlands. Inundation for a long period results in a negative impact on plant growth. The conditions of plant tissue worsen due to the absence of gas exchange rates in stagnant water. Stagnant water causes low oxygen supply, resulting in the fermentation processes in plants [15,16]. Excessive inundation changes physical and chemical processes in the paddy plant. Paddy will elongate the stems or leaves, followed by the yellowing of older foliage, and continue with slow growth [17].

Prolonged excess water is dangerous and causes damage to paddy plants. Crop damage increases the risk of crop failure and decreases rice production. This condition can occur on agricultural land with a high vulnerability to flood hazards [18].

Katingan is located in tidal lowland with zone A and B hydro-topography, influenced by tides during rainy and dry seasons [19]. The constant inundation of land has caused the community to become accustomed to inundation. However, excessive inundation will disrupt the community's livelihood and threaten paddy field production. Therefore, mitigation is needed to decrease disaster risk and negative impact [20].

Inundation control on lowlands can be done from a technical and social perspective. One of the technical controls is the use of pumps. However, in Indonesia, using pumps is very unaffordable due to the high cost. As a result, many lands are inundated and abandoned because using pumps is costly [21]. The use of pumps can be replaced with gates. Gates have a significant influence in controlling the water level in the canals [22]. In Indonesia's Dadahup swampland area, the gates can decrease water levels in the canals and paddy fields [23]. In the Mekong Delta lowland, Vietnam, using gates with embankments prevents flooding due to high tides [12].

The use of gates should consider the hydro-topography of the lowlands. In lowlands with hydro-topography A or B, flap gates are more suitable, while in hydro-topography C or D, sluice gates are more effective in controlling water level [24]. The use of gates that are unsuitable for the characteristics of the lowlands causes a non-optimal gate function.

The construction of gates must be supported by proper operation and maintenance. Good knowledge of the characteristics of the lowlands and consideration of the hydrology process is required to operate the gates efficiently. Maintaining and repairing gates is important for long-term function to control inundated areas [25]. The gates operate depending on tidal and rainfall. At low tide, the gates are opened, while at high tide, the gates are closed. The aim of operating the gates in this method is to retain flood discharge and salinity out of the system [26].

The community should be aware of the hazards of climate change, especially in coastal areas. However, the communities are not convinced that climate change is a significant problem, even though they live in prone areas [27]. In contrast to South Sumatra, the community has adapted to climate change. Farmers have made innovations against floods and droughts. The use of rice seeds is carried out based on field conditions and hydro-topography. They use dry seeds in dry lowlands and plant in large areas. In fields with high water levels, they use floating seeds and are planted using rafts formed from water grass [28].

Structural and non-structural improvements are needed in dealing with extreme climates in the lowlands. Technically, the problems can be solved by improving water structures, land development, smart water management technology, and using rice varieties tolerant of dry and wet climates. Non-structural improvements are conducted by developing information and communication systems, institutional strengthening, and identifying and mapping flood and drought-prone areas [29].

Eight studies have been conducted on the impacts of climate change on coastal areas. Studies related to the impact of sea level rise were conducted on Vietnam's Mekong Delta, but the impact of extreme rainfall was not conducted [12]. Three of them discuss the vulnerability of communities to climate change [10,27,28]. The other three discussed the impact of sea level rise with a broader perspective on coastal areas unspecific to tidal agricultural lowlands [9,11], [13]. The last one discusses the impact of climate change on the decrease in rice production from the El Nino La Nina disasters [29]. There are still limited studies on the impact of tidal overflow and climate change in tidal agricultural lowlands using field measurement and hydrodynamic modeling methods. Therefore, a study was conducted with several objectives to obtain the area, water level elevation, and duration of inundation in paddy fields as an impact of climate change and proposed sustainable water management.

2.0 METHODOLOGY

2.1 Study Area

Katingan is located on the coast of Central Kalimantan, as shown in Figure 3. The downstream water source comes from the tides of the Java Sea, while the upstream comes from the Katingan River. Abundant water resources make Katingan one of the largest rice-contributing regions in Central Kalimantan, but in current conditions, the rice production is low, only 1.5-2.75 tons ha^{-1} [30]. The low rice production initiates the government to improve the existing area and extend it to 8,083 ha. In this research, the study area is an existing paddy field located between secondary canals six left and six right, with an area of 1,871 ha, which can be seen in Figure 4 (white area).

Figure 3 Location of Katingan tidal lowland irrigation area (Base map from OSM Humanitarian Data Model, processed with QGIS 3.28.0)

Figure 4 Study area and automatic water level recorder (AWLR) station (Base map from OSM Humanitarian Data Model, processed with QGIS 3.28.0)

The community of Katingan Tidal Lowlands is diverse from various Indonesian tribes because the opening of Katingan Tidal Lowlands was a transmigration project carried out by the Indonesian government in the 80s [1]. Currently, the number of residents in the Katingan tidal lowlands is 6,539, with the occupation of the community mostly rice farming, with a total of 2,118 households [30], and a minority of trading and swallow breeders [31].

Integrated management of tidal lowlands between technical and social sectors is the solution to increase the resilience of Katingan tidal lowlands to the current uncertain climate. The development of a sustainable water system and the improvement of farmers' capacity in agricultural activities must be done immediately.

2.2 Field Survey

The field survey was conducted to collect fact findings through field measurement, observations, and identification. Field measurements using an automatic water level recorder (AWLR) are presented in Figure 5. The use of automatic water level recorders in lowlands areas has been carried out previously in the Dadahup swamp irrigation area, with an upgrade to a telemetry system [32]. AWLR function to record tidal fluctuation with two units, as shown in Figure 4. The first device was placed in the Katingan River for three months under the name Station 1, while the second device was placed alternately for two weeks in the right primary canal under Station 2 and in the left primary canal under Station 3.

Figure 5 Automatic water level recorder

Field identification was conducted for three months, from December 2022 to March 2023, by observing the tidal overflow events and their impacts on paddy fields. The secondary data collected was annual maximum daily rainfall, which will be used to calculate the rainfall with a 5 and 25-year return period. Land topography is used to compare the elevation of paddy fields with tidal water levels, while hydrometric data is used for canal cross-sections. Indonesia sea level rise data was used to analyze the impact of inundation conditions after 25 and 50 years of sea level rise on Katingan tidal lowlands.

2.3 Hydrodynamic Analysis

The primary analysis is unsteady flow modeling with HEC-RAS. Modeling floods and inundations in HEC-RAS has been widely practiced. In Indonesia's Dadahup swamp irrigation area, paddy fields were modeled with the two-dimensional flow and canals with the one-dimensional flow. The water flow modeling includes tides and rainfall but does not include sea level rise [23]. Flood modeling was also conducted in the Tikurwha river catchment, Ethiopia, using a two-dimensional water flow modeling with steady flow data [33].

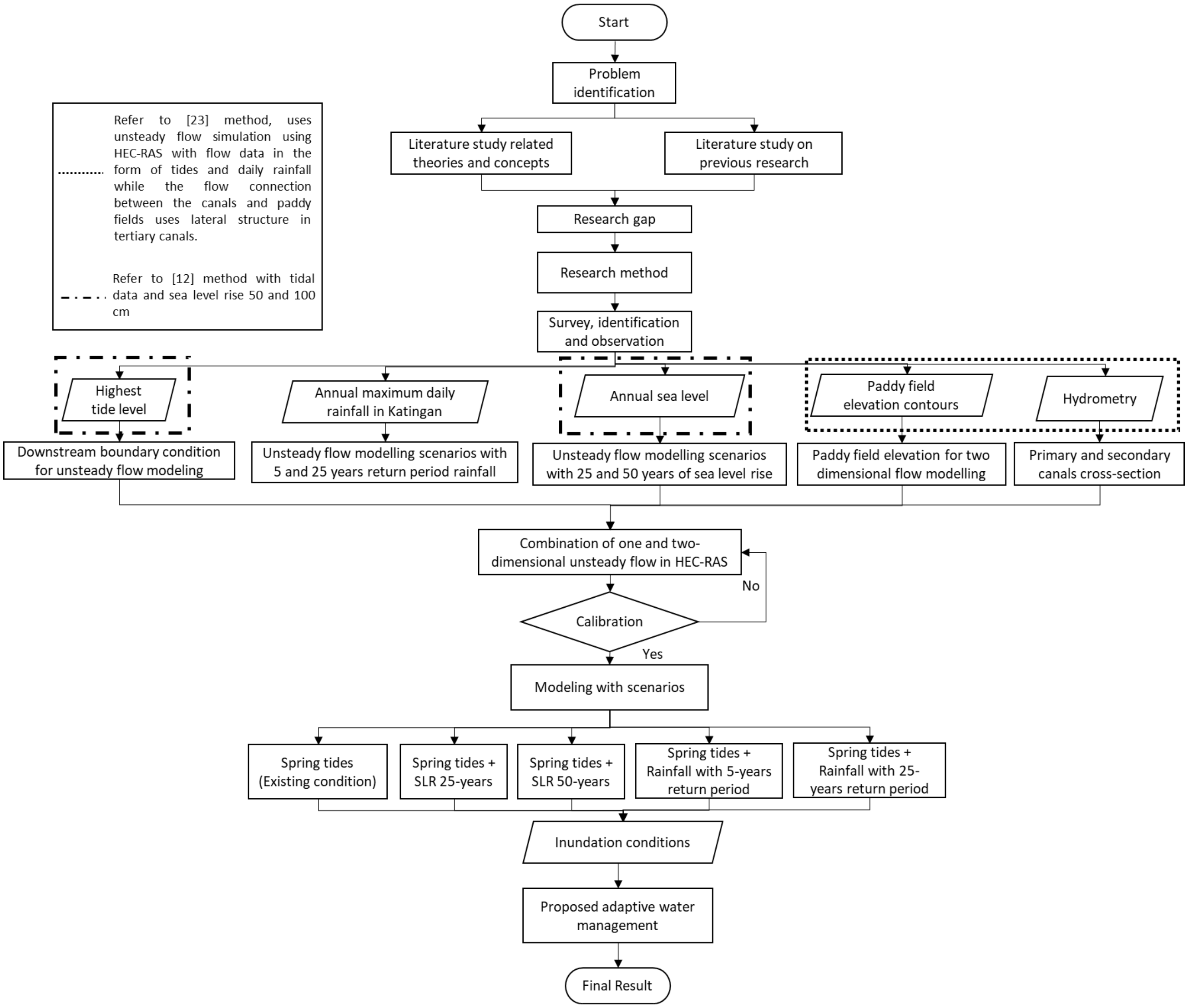


Figure 6 Research methods

Inundation modeling in the lowlands was also conducted in the Mekong Delta of Vietnam. The modeling uses several scenarios related to sea level rise of 50 cm and 100 cm [12]. However, the simulations did not include increased extreme rainfall.

Figure 6 shows that the unsteady flow modeling in HEC-RAS requires canal geometry and flow data to simulate inundation conditions in paddy fields. The cross-section of the canals is obtained from secondary data measuring elevations carried out by the consultant of the Katingan lowlands irrigation project [31], while the flow data uses the tidal and discharge measurements.

Unsteady flow modeling was conducted in three scenarios: spring tide conditions, sea level rise, and extreme rainfall, as shown in Table 1. In the spring tide condition, upstream boundary data used is discharge, and downstream boundary data is measured tide on February 17-22, 2023. Furthermore, sea level rise scenarios were conducted for 25 and 50 years. Sea level rise will be added to the measured tidal data. The last scenario is extreme rainfall with a 5 and 25-year return period, where rainfall is assumed to fall uniformly on the paddy fields.

Water flow modeling in canals using a one-dimensional flow, while in the paddy fields using a two-dimensional flow. Connection of one- and two-dimensional flows using lateral structures. The lateral structure is located along the secondary canals.

Table 1 Scenarios of unsteady flow simulation using HEC-RAS

No	Scenarios	Tide	Rainfall
1	Existing	Spring tide	-
2	Sea level rise	Spring tide with 25- and 50-year sea level rise	-
3	Extreme rainfall	Spring tide	5 and 25 years return period rainfall

The simulation will be compared with field measurements for modeling calibration. Calibration is conducted by changing the value of n-manning in the canals and paddy fields. The calibrated unsteady flow simulation results will be used to model sea level rise and extreme rainfall scenarios.

3.0 RESULTS AND DISCUSSION

3.1 Field Study and Measurements

Field identification shows that tidal overflow occurs at spring tide conditions. The tidal overflowed into the paddy fields on February 17-19, 2023. This condition caused the inundation of paddy fields, access roads, and settlements, as seen in Figure 7.

(a) (b) (c)

Figure 7 Tidal inundation in (a) paddy fields, (b) settlements, and (c) access roads

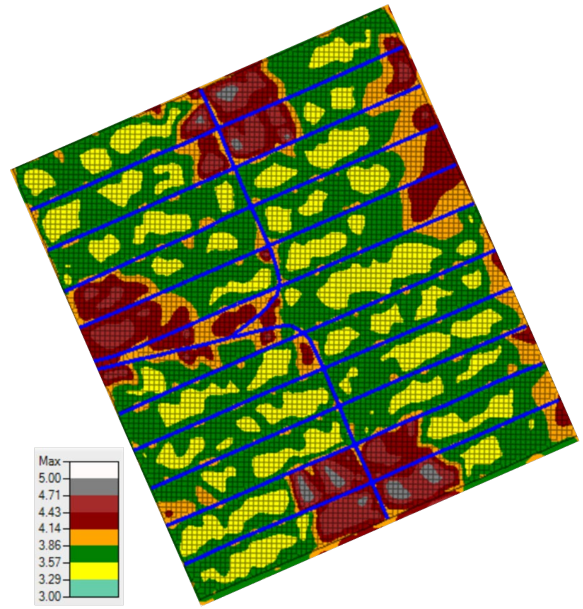


Figure 8 Paddy fields elevation in Katingan tidal lowland (Base map from terrain 2d in HEC-RAS)

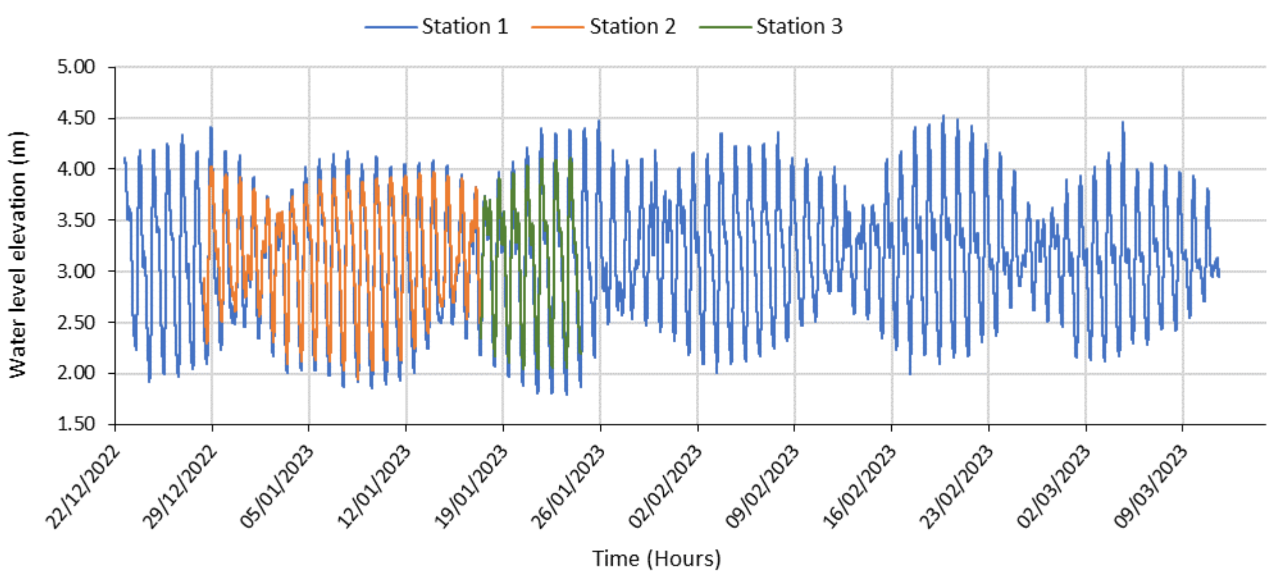


Figure 9 Comparison of water level elevations at stations 1,2 and 3

Figure 9 shows that February 17-20, 2023, was the highest tide from December 2022 to March 2023 in station 1 (Katingan River). The highest water level recorded on February 19, 2023, at 05.00 pm, was +4.52 m, while the elevation of paddy fields was only at +3.20-3.80 m, as seen in Figure 8. This condition causes tidal overflow to the paddy fields, similar to the findings in the field in Figure 7.

In the gauging station 2 (right primary canal), measurements were taken from December 28, 2022 - January 17, 2023. The highest water level was at +4.03 m on December 28, 2022, at 11 pm. Meanwhile, in the gauging station 3 (left primary canal), the highest water level was at +4.10 m from January 17-24, 2023.

Tidal overflow affects paddy fields and residents. Figure 7 shows the activities of residents disrupted by tidal overflow. Tidal overflow needs to be controlled. Short-term control can use gates and digging up existing canals. Proper planning is needed so that tide control is conducted effectively.

3.2 Sea Level Rise

Based on sea level observations in Indonesia from 1993 to 2015 [6], there is an anomaly in sea level annually, as shown in Figure 10. The calculation of sea level rise is conducted by analyzing the trendline of sea level; thus, the sea level rise in Indonesia is 4.9 mm years^{-1}. In 25 and 50 years, the sea level rise in Indonesia reached 0.12 m and 0.24 m, as shown in Table 2.

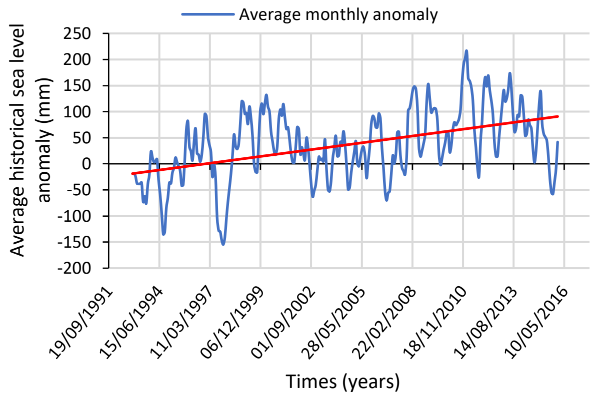


Figure 10 Sea level in Indonesia based on observed anomalies relative to mean from 1993 – 2015 [6]

Table 2 Prediction of sea level rise based on the data analysis of historical sea level rise in Indonesia

No	Years		Projected Sea Level Rise (mm)
1	0	2023	0
2	25	2048	121
3	50	2073	243

The most influential areas impacted by sea level rise are near the coast [34]. Tidal lowlands located on the coast will have a high risk of being impacted by sea level rise. The impact of discharge from upstream rivers will be decreased due to increased tidal influence from downstream rivers. Another impact is hydro-topography changing in tidal lowlands, from hydro-topography B to A or category C to B or even A [34]. The hydro-topography change will decrease the land's drainage ability [34].

Katingan tidal lowlands have a high risk of being impacted by sea level rise. This risk is due to several factors, including the location of the lowland close to the coast, the low hydro-topography of the land, and the frequent overflow of tides on the land during spring tide.

The impact of sea level rise on Katingan tidal lowland simulated in HEC-RAS. The simulation aims to identify the inundation conditions in the next few years to be the preliminary measure in anticipating sea level rise; then, it can apply a water management system that can decrease the risk of sea level rise impacts in Katingan tidal lowlands.

3.3 Simulation Results of Spring Tide Conditions

In the spring tide conditions, paddy fields are inundated due to tidal overflow, as seen in Figure 11. The inundation area reached 1,373.60 ha or 73.42%. The observation in the paddy fields showed the same inundation conditions as the simulation results. In Figure 12, the tidal overflow becomes uncontrollable, inundating the paddy fields.

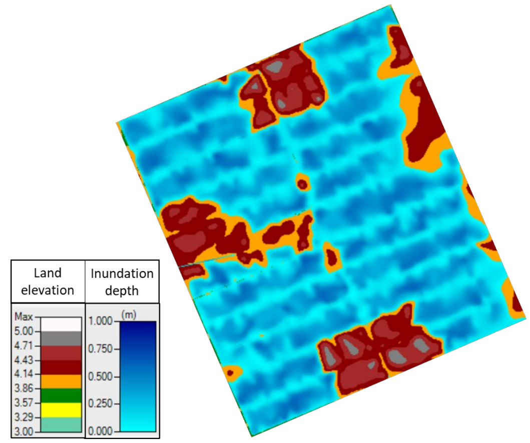


Figure 11 Topographic contours of paddy fields and depth of inundation in spring tide conditions

Figure 12 Inundation on paddy fields due to spring tide conditions

3.4 Inundation Under 25- and 50-Year Sea Level Rise Conditions

Sea level rise increases the inundation in the paddy fields. Figure 13 and Figure 14 show that under a 25-year sea level rise, the inundation area reaches 1,392.12 ha or 74.41%, while under a 50-year sea level rise, the inundation area reaches 1,400.67 ha or 74.86%.

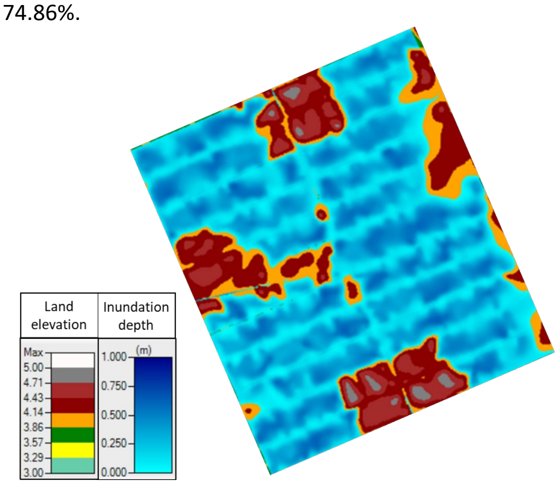


Figure 13 Topographic contours of paddy fields and inundation depth due to 25-year sea level rise

The inundation area analysis was classified into four categories based on depth, namely 0.00-0.20 m, 0.20-0.40 m, 0.40-0.60 m, and greater than 0.60 m depth. This classification is based on the water level requirements for rice crops. A larger inundation area in a paddy field is not certainly dangerous for rice crops but is dangerous when the inundation depth is excessive. Several references state the optimal inundation depth for rice crops. The threshold of inundation depth for rice crops is 0.32 m [35], while [36] states that inundation of more than 0.20 m will result in crop failure. In [19] state, rice crops' inundation depth at 0.00-0.25 m is cultivable. The hazard of inundation in paddy fields is not based on the area but on the depth of inundation; therefore, the analysis is grouped based on the depth of inundation.

Under sea level rise, the total inundation area increased but insignificantly; this causes the Katingan tidal lowland located in hydro-topography A and B, so the land is constantly inundated in the rainy or dry season [19,30]. Thus, adding tidal overflow discharge to paddy fields insignificantly increases the total inundation area. In Table 3, the inundation area increases at higher depths. Inundation area at depths of 0.40-0.60 m increased from 244.64 ha under spring tide to 300.60 ha and 328.66 ha under sea level rise 25 and 50 years; meanwhile, at depths 0.00-0.20 m and 0.20-0.40 m, inundation area decreased.

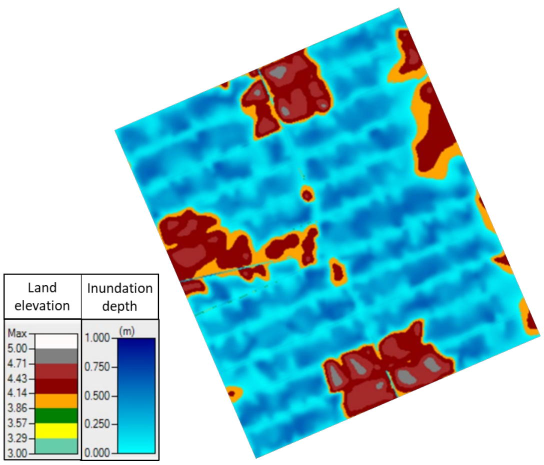


Figure 14 Topographic contours of paddy fields and inundation depth due to 50-year sea level rise

Table 3 Comparison of inundation area due to spring tide and sea level rise

No	Depth (m)	Inundation area (ha)		
		Spring tide	Sea level rise 25-years	Sea level rise 50-years
1	0.00-0.20	584.12	547.04	528.18
2	0.20-0.40	544.78	542.33	539.52
3	0.40-0.60	244.64	300.60	328.66
4	>0.60	0.06	2.15	4.31
	Total	1,373.60	1,392.12	1,400.67

3.5 Inundation Under Rainfall with 5 and 25- Years Return Period

Inundation in paddy fields increased due to rainfall. Figure 15 shows that under rainfall with a 5-year return period, inundation reaches 1,481.61 ha or 79.19%. Meanwhile, under rainfall with a 25-year return period, the inundation reached 1,481.93 ha or 79.21%, as presented in Figure 16.

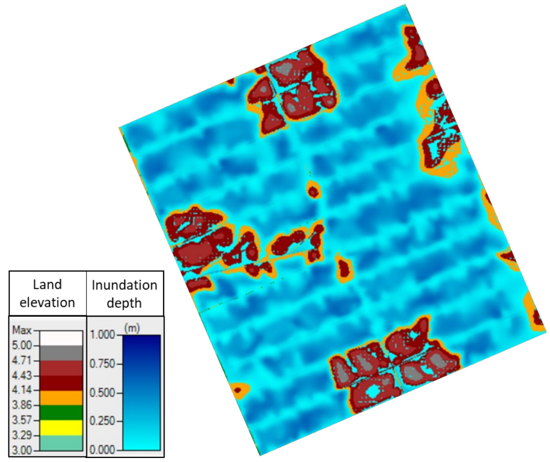


Figure 15 Topographic contours of paddy fields and depth of inundation due to rainfall with a 5-year return period

Due to rainfall in paddy fields, the most significant increase in the inundation depth is 0.00-0.20 m, as presented in Table 4. This condition occurs because the rain uniformly falls on the paddy field so that the land that was not inundated will inundated after the rainfall; this condition occurs on land with high elevation.

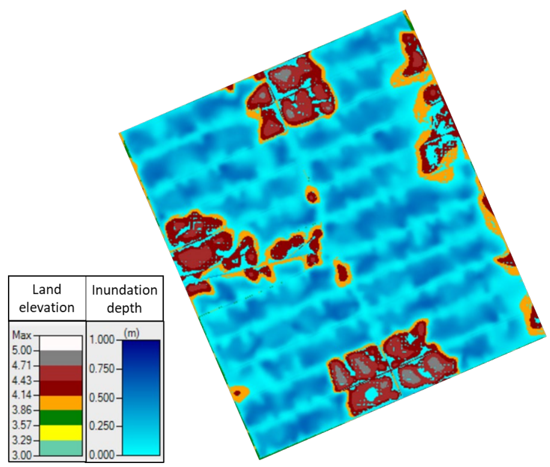


Figure 16 Topographic contours of paddy fields and depth of inundation due to rainfall with a 25-year return period

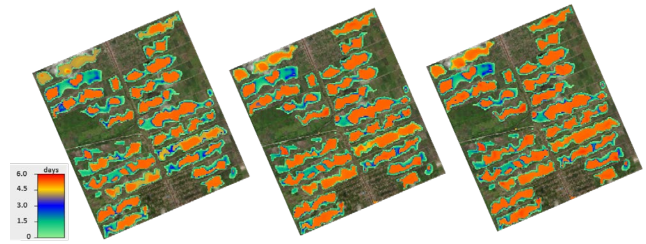
Table 4 Comparison of inundation area due to spring tide and rainfall with 5 and 25-year return period

No	Depth (m)	Inundation area (ha)		
		Spring tide	Rainfall with a 5-year return period	Rainfall with a 25-year return period
1	0.00-0.20	584.12	670.03	664.35
2	0.20-0.40	544.78	546.11	545.90
3	0.40-0.60	244.64	265.10	271.03
4	>0.60	0.06	0.37	0.65
	Total	1,373.60	1,481.61	1,481.93

3.6 Duration and Depth of Inundation

The optimum growth for rice crops depends on the quantity of water and the duration of inundation. Inundation of more than three days with a depth of more than 0.20 m results in crop failure [37]; therefore, inundation duration analysis is needed to determine the impact of sea level rise and extreme rainfall on the inundation duration in paddy fields.

Sea level rise and extreme rainfall increase the inundation duration on paddy fields; this can be seen in Figure 17 and Figure 19. Similar to the study in Vietnam's Mekong Delta, sea level rise increases the area and depth of inundation [12]. Unsteady flow simulation shows, under spring tide conditions, the average duration of inundation in paddy fields is 3.11 days, while under sea level rise in 25 and 50-year increases to 3.28 and 3.40 days.



(a) (b) (c)

Figure 17 Comparison of the average inundation duration in paddy fields under (a) spring tide and (b) 5 and (c) 25 years return period rainfall

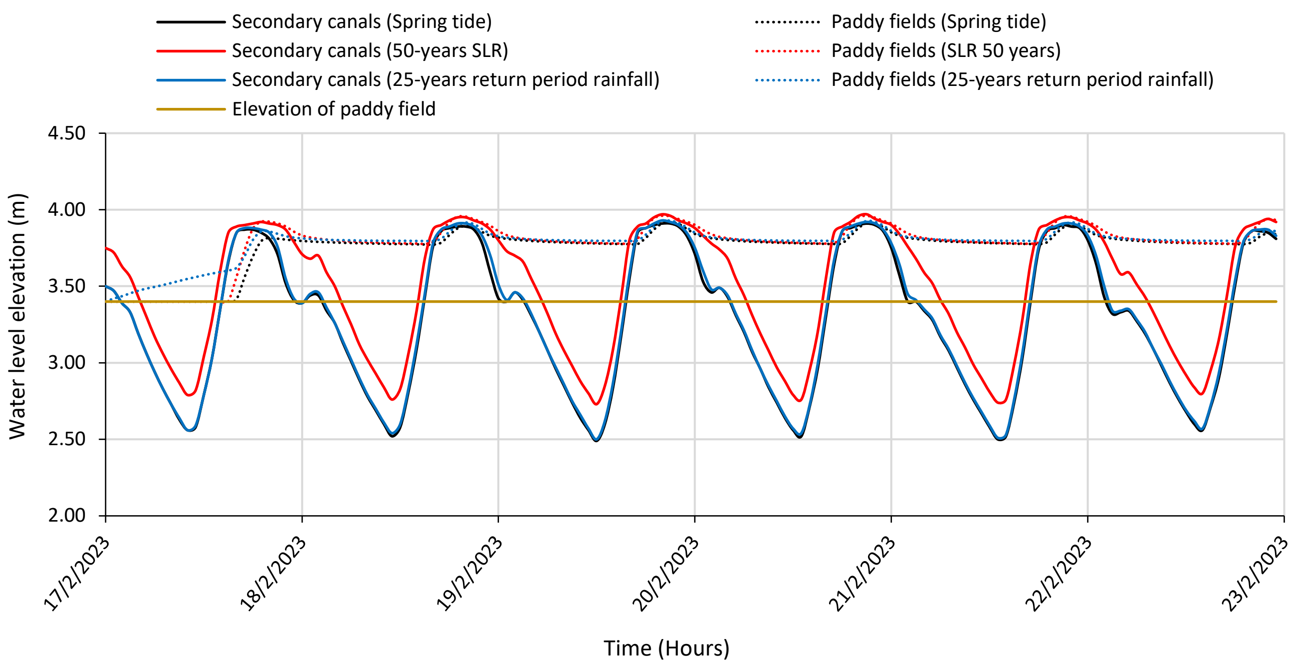
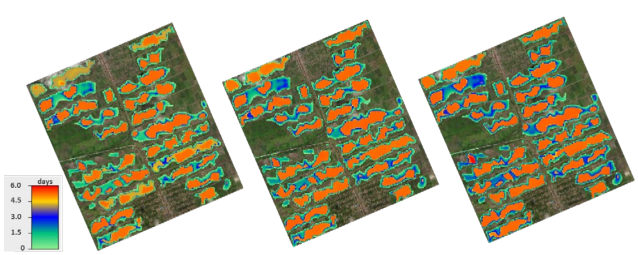


Figure 18 Comparison of water levels in secondary canals and paddy fields under spring tide, 50-year sea level rise, and rainfall with a 25-year return period

Meanwhile, under rainfall with a return period of 5 and 25-years, the duration of inundation on the paddy fields is 3.40 and 3.48 days.



(b) (b) (c)

Figure 19 Comparison of the average inundation duration in paddy fields under (a) spring tide and (b) 25 and (c) 50 years of sea level rise.

The water level elevation on the paddy fields is higher than in the canals, so tidal water will be more difficult to drain. Figure 18 shows that the water level in the paddy fields and the canals is the same at high tide due to the overflow. At low tide, the water level elevation in paddy fields decreases but does not reach the ground surface; thus, paddy fields are constantly inundated at elevation +3.70—3.80 m.

The duration of inundation in paddy fields is more than three days with a depth of more than 0.20 m, which will cause crop failure [37]. Increased water levels in paddy fields impact changes to hydro-topography and water management zoning [34]. Therefore, controlling inundation in paddy fields is necessary to decrease the area, water level, and duration of inundation.

3.7 Proposed Sustainable Water Management System

A sustainable water management system is needed to control the excessive inundation in paddy fields. Excessive tidal overflow should be reduced, and maintain the water level at the rice growth root zone. Water levels in the canals can be controlled by the gates' operation, as presented in Figure 20. Operation and maintenance of gates are important to maintain the sustainability of the water system.

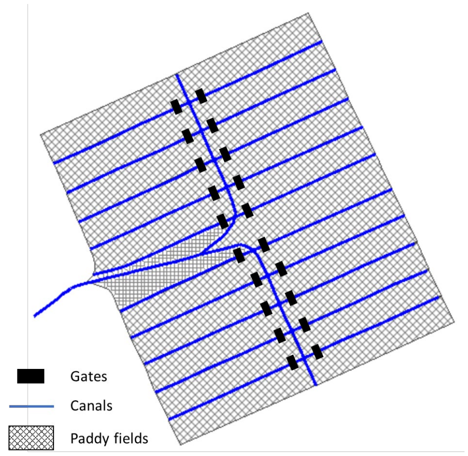


Figure 20 Use of gates on secondary canals

Uncontrolled tides in the canals will inundate the paddy fields, as seen in Figure 21. Preventive actions and improvement of the water system should be conducted by short and long-term methods. In the short term, improvements in water systems such as gates, canal excavation, flood embankments, and drain pipes can be carried out, as presented in Figure 22.

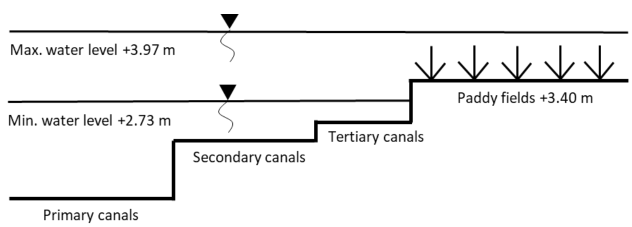


Figure 21 Water level in canals and paddy fields without controls due to 50-year sea level rise

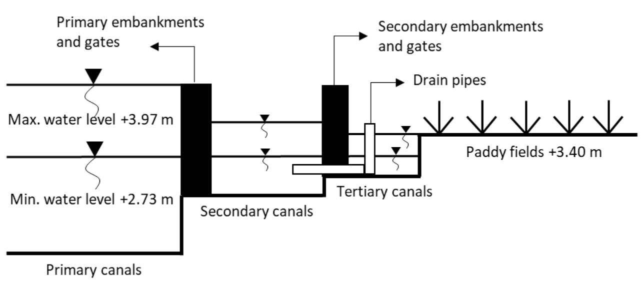


Figure 22 Water level in canals and paddy fields with controls due to 50-year sea level rise

A proper macro water management system is needed in the long-term solutions. The water management system addressed technical and social issues. Integration between government sectors and local communities is needed to support the sustainability of Katingan tidal lowlands. Local farmers must be involved in maintaining the sustainability of paddy fields by increasing farmers' knowledge and awareness of the hazards of climate change.

4.0 CONCLUSION

Katingan tidal lowlands are inundated due to spring tide conditions. Inundated caused by tidal overflow from canals to paddy fields. From the tide measurements, the water level in the canals was at +4.52 m while the paddy fields elevation was at +3.20-3.80 m; thus, the tide constantly overflows into paddy fields at high tide. The inundation will worsen in the next few years due to rising sea levels and extreme rainfall. The unsteady flow simulation with HEC-RAS shows an increase in the area, water level, and duration of inundation.

During spring tide, the inundation area is 73.42% of the study area. Under sea level rise of 25 and 50 years, the inundation area increases to 74.41% and 74.86%. Meanwhile, under rainfall with a 5 and 25-year return period, the inundation area reaches 79.19% and 79.21%.

Sea level rise and extreme rainfall also increase the inundation duration and water level on paddy fields. Under spring tide conditions, the inundation duration reaches 3.11 days, while under sea level rise in 25 and 50-year increases to 3.28 and 3.40 days. Under rainfall with a return period of 5 and 25- years, the duration of inundation on the paddy fields is 3.40 and 3.48 days. Paddy fields are continuously inundated at elevations of +3.70-3.80 m, while the elevation of paddy fields is only +3.40 m.

Excessive inundation with prolonged periods leads to damage and decreased rice production. Preventive actions and water system improvement should be conducted to control the inundations in paddy fields. Sustainable water management should consider technical and social issues. In the short-term solution, inundation control can be conducted using gates, canal excavation, flood embankments, and drain pipes. Meanwhile, in the long-term, integration between government sectors and local communities is needed to support the sustainability of Katingan tidal lowlands. Local farmers must be involved in maintaining the sustainability of paddy fields by increasing farmers' knowledge and awareness of climate change hazards.

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