

ASSESSING FLOOD-INDUCED SALINITY RISKS IN COASTAL IRRIGATION SYSTEMS USING INUNDATION ANALYSIS AND WATER QUALITY DATA: A CASE STUDY OF INDRAMAYU, INDONESIA

ÉVALUATION DES RISQUES DE SALINITE INDUITS PAR LES INONDATIONS DANS LES SYSTEMES D'IRRIGATION COTIERS A L'AIDE D'ANALYSES D'INONDATION ET DE DONNEES SUR LA QUALITE DE L'EAU : UNE ETUDE DE CAS D'INDRAMAYU, EN INDONESIE

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ABSTRACT

Coastal agricultural regions in Indonesia, especially along the northern coast of Java, are facing heightened pressures from tidal flooding, sea-level rise, land subsidence, and saltwater intrusion, jeopardizing the viability of irrigated rice cultivation. Indramayu Regency, situated on the northern coast of West Java, is a prominent agricultural region due to its irrigation infrastructure often facing tidal inundation and saltwater encroachment from coastal and estuarine systems. Although awareness of coastal flood threats is growing, there remains a scarcity of research that explicitly combines flood exposure mapping with assessments of irrigation water quality to estimate salinity risks impacting agricultural output. This study seeks to evaluate the salinity risk from flooding in the Indramayu coastal irrigation system by inundation analysis integrated with spatial and temporal water quality assessments from irrigation canals and adjacent rice fields.

A numerical flood model utilizing a digital elevation model (DEM) was employed to simulate coastal flood inundation zones under various tidal water level scenarios. DEM pre-processing encompassed basin filling, elevation correction, and slope normalization to enhance the depiction of flood extent. Further, utilizing sea level data for typical high tides, extreme tidal occurrences, and future projection sea-level rise scenarios as downstream boundary conditions, a flood exposure map is produced, which is further employed to identify irrigation infrastructure and agricultural regions susceptible to coastal flooding. The water quality evaluation emphasizes metrics associated with water salinity, such as electrical conductivity (EC) and total dissolved solids (TDS), along with acidity (pH) as an ancillary indicator. Additionally, this water quality data is utilized to apply an IDW spatial interpolation technique for the creation of a salinity distribution map within the irrigation area, while a statistical correlation analysis is conducted to investigate the relationship between flood exposure levels and salinity concentrations in irrigation water and the rice field environment.

The analysis reveals that irrigation zones in coastal regions are significantly susceptible to tidal flooding, particularly under extreme tidal circumstances and anticipated sea-level rise scenarios. The spatial relationship between flood-prone regions and elevated salinity levels demonstrates that frequent tidal flooding substantially facilitates saltwater intrusion into irrigation canals and agricultural fields. Regular elevations in EC and TDS levels were noted in regions subjected to regular irrigation, suggesting a possible decline in the appropriateness of irrigation water for rice agriculture. These findings underscore the significance of coastal flooding not merely as a hydrological threat but also as a catalyst for the deterioration of irrigation water quality and the increased danger of soil salinity.

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This study assessed the ramifications for irrigation system resilience, encompassing diminished water appropriateness, heightened risk of soil salinization, and potential effects on agricultural yield. Following this assessment, adaptation measures were developed, encompassing improved drainage management, optimization of tidal gates, enhanced monitoring of irrigation water quality, and the incorporation of flood risk data into irrigation planning.

This study offers a comprehensive and cohesive method for assessing the relationships between coastal flooding and salinity that impact irrigated agriculture. This approach enhances decision-making for irrigation management in coastal agricultural systems experiencing heightened climate and environmental challenges, especially in delta regions and coastal lowlands equivalent to Indramayu.

Keywords: Coastal flooding, sea water intrusion, coastal irrigation system, north coast of Java.

RESUME

Les régions agricoles côtières en Indonésie, en particulier le long de la côte septentrionale de Java, sont confrontées à des pressions accrues dues aux inondations par les marées, à l'élévation du niveau de la mer, à l'affaissement des terres et à l'intrusion d'eau salée, ce qui compromet la viabilité de la culture de la riziculture irriguée. Le kabupaten d'Indramayu, située sur la côte septentrionale de Java occidentale, est une région agricole de premier plan en raison de son infrastructure d'irrigation souvent confrontée à des inondations par les marées et à l'infiltration d'eau salée par les systèmes côtiers et estuariens. Bien que la prise de conscience des menaces liées aux inondations côtières progresse, il existe peu de recherches qui combinent explicitement la cartographie de l'exposition aux inondations avec les évaluations de la qualité de l'eau d'irrigation pour estimer les risques de salinité exerçant un impact sur la production agricole. Cette étude vise à évaluer le risque de salinité lié aux inondations dans le système d'irrigation côtier d'Indramayu par une analyse des inondations intégrée aux évaluations spatiales et temporelles de la qualité de l'eau des canaux d'irrigation et des rizières adjacentes.

Un modèle numérique d'inondation utilisant un modèle numérique d'élévation (MNE) a été utilisé pour simuler les zones d'inondation côtière dans le cadre de divers scénarios de niveau d'eau de marée. Le prétraitement du DEM a englobé le remplissage du bassin, la correction de l'élévation et la normalisation de la pente afin d'améliorer la représentation de l'étendue des crues. En outre, en utilisant des données sur le niveau de la mer pour les marées hautes typiques, les événements de marée extrêmes et les scénarios de projection future d'élévation du niveau de la mer comme conditions limites en aval, une carte d'exposition aux inondations est produite, qui est en outre utilisée pour identifier les infrastructures d'irrigation et les régions agricoles sensibles aux inondations côtières. L'évaluation de la qualité de l'eau met l'accent sur les mesures associées à la salinité de l'eau, telles que la conductivité électrique (CE) et les matières dissoutes totales (TDS), ainsi que l'acidité (pH) comme indicateur auxiliaire. De plus, ces données sur la qualité de l'eau sont utilisées pour appliquer une technique d'interpolation spatiale IDW afin de créer une carte de répartition de la salinité dans la zone d'irrigation, alors qu'une analyse de corrélation statistique est menée pour étudier la relation entre les niveaux d'exposition aux inondations et les concentrations de salinité dans l'eau d'irrigation et l'environnement des rizières.

L'analyse révèle que les zones d'irrigation dans les régions côtières sont particulièrement sensibles aux inondations par les marées, en particulier dans des circonstances de marée extrêmes et selon des scénarios prévus d'élévation du niveau de la mer. La relation spatiale entre les régions sujettes aux inondations et les niveaux de salinité élevés démontre que les inondations par les marées fréquentes facilitent considérablement l'intrusion d'eau salée dans les canaux d'irrigation et les champs agricoles. Des élévations régulières des niveaux de conductivité électrique (EC) et des matières dissoutes totales (TDS) ont été notées dans les régions soumises à une irrigation régulière, suggérant une baisse potentielle de la justesse de l'eau d'irrigation pour la riziculture. Ces résultats soulignent l'importance des inondations côtières non seulement en tant que menace hydrologique, mais aussi comme catalyseur de la détérioration de la qualité de l'eau d'irrigation et du danger accru de la salinité des sols.

Cette étude a évalué les ramifications pour la résistance du système d'irrigation, englobant la moindre justesse de l'eau, le risque accru de salinisation des sols et les effets potentiels sur le rendement agricole. À la suite de cette évaluation, des mesures d'adaptation ont été mises au point, comprenant la meilleure gestion du drainage, l'optimisation des clapets à marée, la surveillance accrue de la qualité de l'eau d'irrigation et l'intégration des données sur les risques d'inondation dans la planification de l'irrigation.

Cette étude propose une méthode complète et cohérente pour évaluer les relations entre les inondations côtières et la salinité qui exercent un impact sur l'agriculture irriguée. Cette approche facilite la prise de décision concernant la gestion de l'irrigation dans les systèmes agricoles côtiers confrontés à des défis climatiques et environnementaux accrus, en particulier dans les régions deltaïques et les basses terres côtières similaires à Indramayu.

Mots-clés : Inondation côtière; Intrusion d'eau de mer; Système d'irrigation côtier; Côte septentrionale de Java.

INTRODUCTION

Irrigated agriculture in coastal areas plays a crucial role in supporting food security, as fertile lowland areas are generally concentrated near river deltas and coastal plains. Geographically located along the northern coastline of Java Island, the North Coast of Java is one of the most productive regions in Indonesia. Rich in natural resources and high economic potential, the North Coast supplies a significant portion of national rice production, thus establishing itself as a national food security region. However, coastal agricultural systems are increasingly threatened by various environmental pressures, including land subsidence, sea level rise, which exacerbates tidal flooding, and saltwater intrusion.

The combination of climate change, sea level rise, and human activities is increasing the extent, frequency, and extent of seawater intrusion in lowland coastal agricultural areas (**Kumar M. et al., 2024; Menten et al., 2023; Musallam et al., 2023; Siemes et al., 2025; Tharik & Vijayaraghavalu, 2024**). Coastal flooding not only damages agricultural infrastructure but also facilitates the movement of saltwater into irrigation networks and agricultural land in coastal areas, potentially reducing crop productivity and even threatening long-term agricultural sustainability (**Oelviani et al., 2024; Tharik & Vijayaraghavalu, 2024**). This indicates that coastal irrigation systems face a dual challenge: maintaining water availability while maintaining water quality suitable for crop production.

Many studies have focused on coastal flooding through hydrodynamic modeling and inundation mapping (**Anjar Dimara Sakti et al., 2025; Johnston et al., 2021; Purnomo et al., 2023, 2025**), while other studies have focused on monitoring seawater intrusion and groundwater quality (**Kumar M. et al., 2024; Sahana & Waspodo, 2020; Tharik & Vijayaraghavalu, 2024**). Most flood studies primarily evaluate inundation area, flood depth, and flood exposure to irrigation infrastructure, without assessing their implications for irrigation water quality (**Koks et al., 2023**). Conversely, studies on seawater intrusion generally examine water quality conditions without explicitly considering flood exposure as a driver influencing the distribution of seawater intrusion. Consequently, understanding how flood exposure patterns can influence spatial and temporal variations in salinity in coastal irrigation systems remains very limited. Therefore, an integrated framework that combines flood inundation analysis with water quality evaluation is needed to better quantify the risk of water salinity distribution and support evidence-based adaptation planning in coastal agricultural areas. Indramayu Regency, located on the north coast of West Java, is an ideal case study to investigate the interaction between coastal flooding and salinity in irrigated areas. Indramayu Regency is one of Indonesia's main rice-producing regions and has been designated as a supporting area for national food security. Its spatial layout features extensive irrigated rice fields supported by a complex irrigation network. Water sources in Indramayu include surface water and groundwater. However, like other coastal areas in Java, despite its agricultural importance, Indramayu frequently experiences tidal flooding associated with high tides in its coastal areas. Furthermore, this area is vulnerable to saltwater intrusion, both into groundwater (**A F Rusydi et al., 2022**), and through irrigation channels, estuaries, and irrigation canals connected to coastal waters. This situation creates significant challenges for irrigation management and agricultural productivity,

especially under future climate change scenarios that raise sea levels.

This study aims to assess the risk of salinity due to flooding in the irrigation system in the coastal area of Indramayu Regency using an integrated approach, combining inundation modeling and water quality analysis, thus providing a comprehensive framework for evaluating salinity risk in coastal irrigation systems.

STUDY AREA

Geographic Setting

Indramayu Regency is located on the north coast of West Java Province, one of Indonesia's most important agricultural producers, and boasts a 147-kilometer coastline. Situated in a coastal lowland directly connected to the Java Sea, Indramayu Regency is highly vulnerable to coastal hazards, including tidal flooding, sea level rise, and saltwater intrusion. Indramayu Regency has a gently sloping topography with an average slope of 0–2%, facilitating the spread of tidal water inland during coastal flooding. The coastal area of Indramayu boasts an extensive network of rivers, irrigation canals, and rice fields. According to the Indramayu Regency spatial plan for 2024–2044, a large portion of the Regency is designated for food crops. However, in recent years, Indramayu's coastal area has been under pressure from climate factors, including sea level rise and increasingly frequent coastal flooding. During high tides, seawater can reach upstream through irrigation canals, increasing the risk of saltwater intrusion into agricultural areas.

Irrigation System Characteristics

The irrigation system in Indramayu plays a crucial role in maintaining national food security. In 2024, Indramayu Regency produced 1,623,459.57 tons of rice (Department of Food Security and Agriculture, 2025), contributing 18.82% of the rice crop in West Java Province and 3.05% of Indonesia's rice crop. The study area has a well-developed network of primary, secondary, and tertiary irrigation canals, distributing water from upstream river systems to agricultural lands along the coastal plains.

However, because the irrigation system is close to the coastline and estuaries, parts of it are directly affected by tidal fluctuations. During extreme tidal events and coastal flooding, saltwater can enter the irrigation canals through river estuaries, drainage canals, and other canal systems at low elevations. This can reduce the quality of irrigation water and increase the risk of salinization of agricultural land in the Indramayu irrigation area. Irrigation infrastructure in the study area consists of open channels, control gates, drainage channels, and water distribution structures. Although these facilities are designed to regulate freshwater distribution for agricultural purposes, they are threatened by saltwater intrusion due to coastal flooding. The vulnerability of the irrigation system is further exacerbated by the low and flat topography and the limited natural barriers that prevent seawater from moving inland. A map of Indramayu Regency is shown in **Figure 1**.

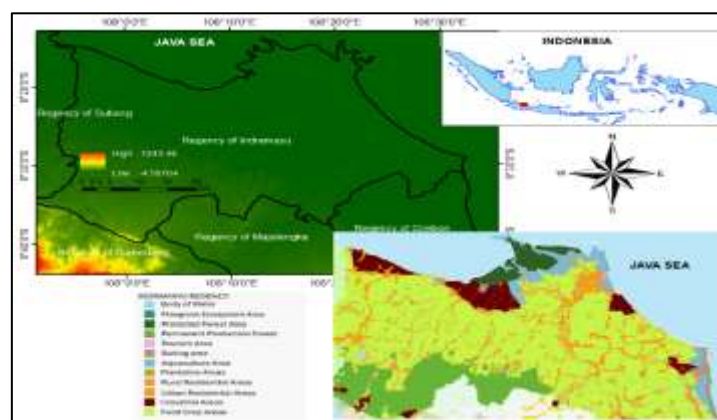


Figure 1. Study Area

Climatic and Hydrological Conditions

Like other climates and climatology in Indonesia, Indramayu's climate is classified as a tropical monsoon climate. Hydrologically, the Indramayu region is influenced by river discharge and coastal tidal processes, creating a complex interaction between freshwater and seawater systems. The combination of low-lying topography, tidal influence, and intensive agricultural land use makes this study area sensitive to salinity caused by flooding.

MATERIALS AND METHODS

Research Framework

This study of seawater intrusion risk due to flooding in the coastal area of Indramayu used an integrated approach, consisting of four main stages: flood inundation modeling, water quality assessment, spatial mapping of water salinity, and statistical analysis of the relationship between flood exposure and salinity indicators.

In the flood inundation modeling, a Digital Elevation Model (DEM) was used and processed by integrating several tidal scenarios. The first scenario used current extreme tidal data, while the second scenario projected sea level rise. Next, a water quality assessment was conducted based on water quality sample data collected from several irrigation canals and selected agricultural land to evaluate water salinity conditions. The measured parameters were spatially interpolated to produce a water salinity distribution map. Finally, a correlation analysis was conducted to examine the relationship between coastal flood exposure and water salinity levels. The results were then used to formulate adaptation strategies to increase the resilience of irrigation systems to coastal hazards. The research framework for flood-induced salinity risk assessment is shown in **Figure 2**.

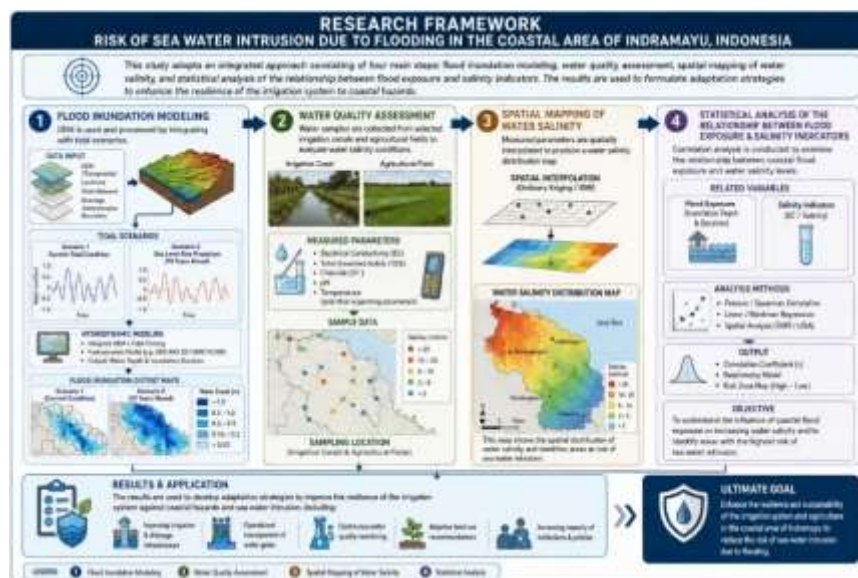


Figure 2. Research framework of flood-induced salinity risk assessment.

Flood Inundation Analysis

Flood inundation modeling was performed using a DEM representing the topographic characteristics of Indramayu Regency. This DEM data was obtained from DEMNAS Indonesia with a spatial resolution of 0.27 arc sec, which is the result of integration of TerraSAR-X, IFSAR, and ALOS PALSAR data. For downstream boundary conditions, simulations were performed under the current extreme flood scenario and the 10-year sea level rise projection was taken from the Indonesian geospatial reference system

from the Geospatial Information Agency dated November 22, 2025 – December 20, 2025. This date was chosen because on December 4, 2025, a fairly high tidal flood occurred in Indramayu Regency. Meanwhile, precipitation data was used as the upstream boundary condition, using rainfall data from NASA POWER on the same date as the tidal data. The flood modeling scheme consisting of the DEM and tidal data is shown in **Figure 3**.

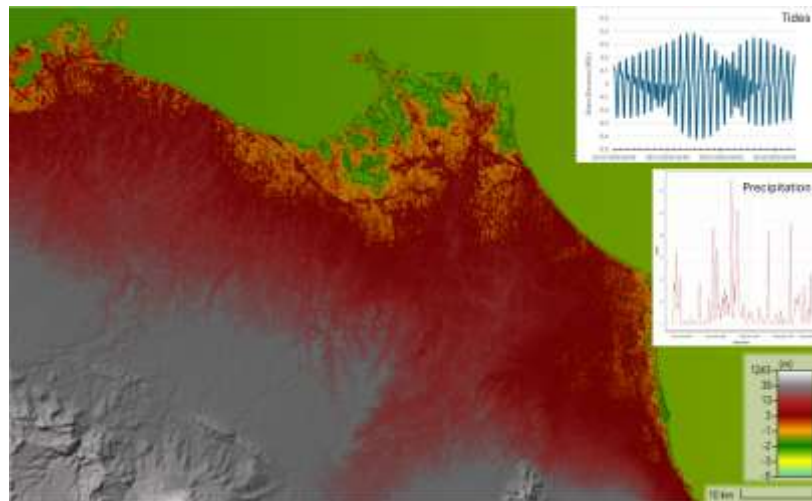


Figure 3. Research framework of flood-induced salinity risk assessment.

Water Quality Assessment

This study used water quality data in agricultural land, irrigation channels, and rivers, in the form of 34 primary data sampling points and secondary data derived from previous studies (Hafiidh et al., 2018; N.R. Herdianita et al., 2008). For primary data, data samples were taken in situ using a water quality meter. Assessments were conducted for parameters related to seawater intrusion, namely Electrical Conductivity (EC), Total Dissolved Solids (TDS), and salinity. Water quality sampling points and irrigation areas in Indramayu Regency are shown in **Figure 4**.

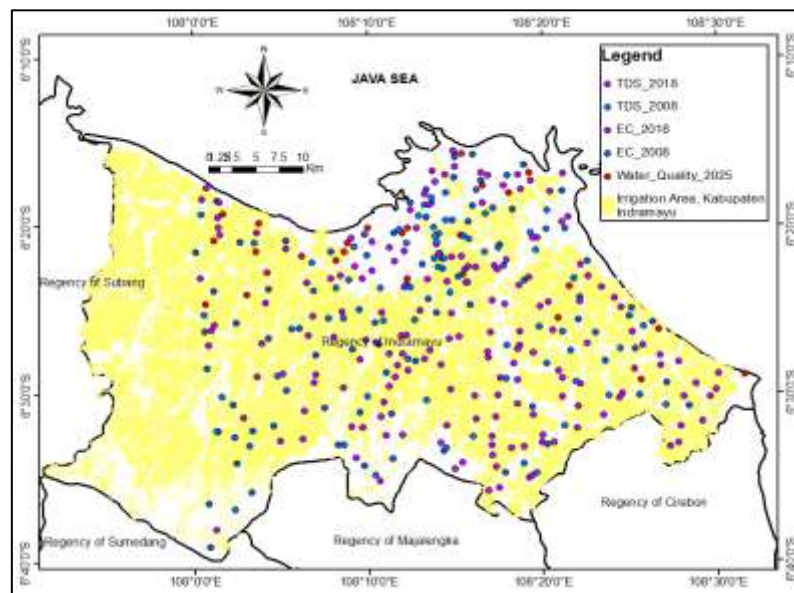


Figure 4. Water quality sampling points and irrigation areas in Indramayu Regency.

After all data is collected, spatial interpolation is performed to estimate the salinity distribution throughout the irrigation system. This study uses the Inverse Distance Weighting (IDW) method, which is suitable for dataset conditions with limited sampling points. This IDW interpolation can estimate salinity values at unsampled locations, based on the weighted influence of nearby observations, so that locations closer to the measurement point will receive a greater influence than locations further away. The IDW equation is shown in Equation 1, where Z_x is the estimated value at location x , Z_i is the observed value at sampling point i , w_i is the distance-based weight, and n is the number of neighboring points

$$Z_x = \frac{\sum_{i=1}^n w_i Z_i}{\sum_{i=1}^n w_i} \quad (1)$$

Statistical Analysis

To determine the effect of coastal flooding on salinity conditions, a statistical correlation analysis was conducted between flood exposure levels and measured water quality parameters. This statistical analysis aimed to determine whether areas experiencing greater flood exposure also exhibited higher salinity concentrations, thus providing quantitative evidence of the risk of flooding-induced salinity in irrigation systems. Flood exposure values were extracted from inundation maps and matched with water quality observations at the sampling locations. Interpretation of the correlation coefficient (r) was performed following conventional criteria, with r values for very weak, weak, moderate, strong, and very strong correlations ranging from 0.00 to 0.19, 0.2 to 0.39, 0.40 to 0.59, 0.60 to 0.79, and 0.80 to 1.00, respectively.

To determine the risk of salinity, this study also conducted a salinity risk classification for EC and TDS values based on water quality guidelines for irrigation (**R.S. Ayers & D.W. Westcot, 1994**), where EC values exceeding 3 dS/m indicate saltwater, values between 0.7 and 3 dS/m denote brackishwater, and values below 0.7 dS/m is freshwater conditions. TDS values over 2000 mg/l indicate saltwater, values ranging from 450 to 2000 mg/l reflect brackishwater, while values below 450 mg/l is freshwater conditions.

RESULTS AND DISCUSSION

Flood Exposure Characteristics

Flood inundation modeling indicates that the coastal areas of Indramayu are highly vulnerable to tidal flooding under all simulation scenarios. The inundation area increases from the existing tidal conditions and the projected sea-level rise scenario. Areas located in the low-lying coastal zone experience the highest level of flood exposure due to their proximity to the coastline and limited topographic relief.

Simulation results indicate that several irrigation canals and agricultural areas are directly affected by coastal flooding, with most irrigated areas exposed to floodwaters. Under the sea-level rise scenario, the inundated area extends further inland, increasing the number of irrigation structures exposed to salty floodwaters. These findings suggest that future sea-level rise due to climate change could significantly increase the vulnerability of coastal irrigation systems in Indramayu.

The observed flooding patterns are consistent with characteristics commonly found in deltaic and lowland coastal environments, where a small increase in the existing tide level compared to the 10-year sea-level rise scenario can result in a substantial change in the flood inundation area of 70,562.21 m². The results of the flood inundation simulation for existing conditions (a) and projections for the next 10 years (b) are shown in **Figure 5**.

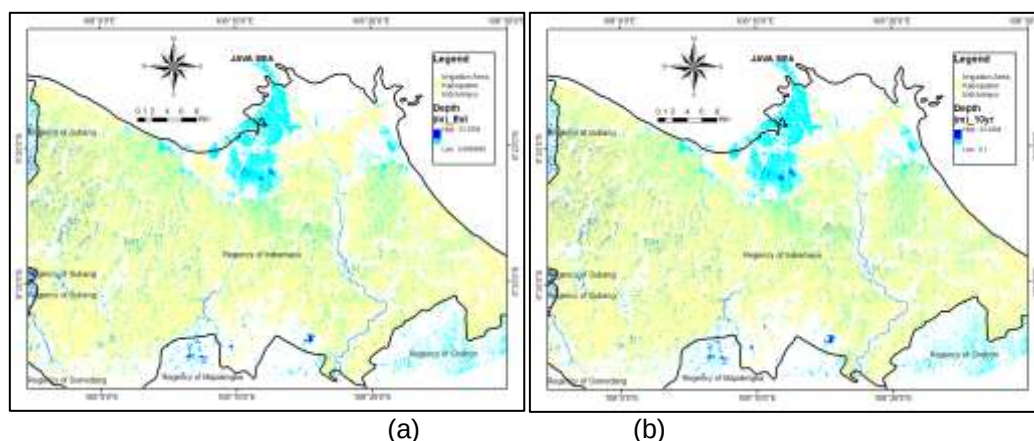


Figure 5. Coastal flooding simulation.

Spatial Distribution of Salinity in Irrigation Water

Water quality analysis revealed significant spatial variability in salinity indicators across the study area. High Electrical Conductivity (EC) and Total Dissolved Solids (TDS) values were generally observed at locations near the coastline and estuary channels, while lower concentrations were found in inland irrigation areas.

IDW interpolation results indicated distinct salinity hotspots within the coastal irrigation network. These areas closely corresponded to zones frequently subject to tidal inundation and direct hydraulic interaction with seawater. Spatial patterns indicated that saltwater intrusion was not uniformly distributed but concentrated along specific pathways associated with tidal channels and irrigation canals.

Based on EC and TDS measurements from 2008 and 2018, the area affected by seawater intrusion has expanded over the past 10 years. Continued exposure to high salinity levels can reduce the suitability of irrigation water and contribute to long-term land degradation.

The results confirm that coastal hydrodynamic processes play a significant role in controlling irrigation water quality. These findings are particularly important for rice cultivation, which is sensitive to prolonged salinity conditions during critical growth stages. Changes in EC and TDS values in 2008 (a) and 2018 (b) are shown in **Figures 6 and 7**.

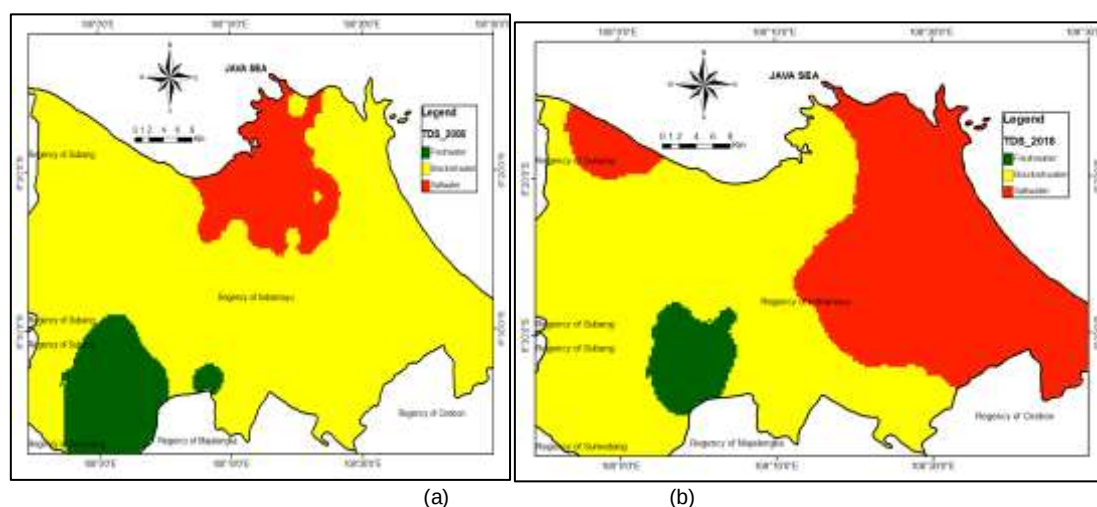


Figure 6. Spatial Distribution of TDS.

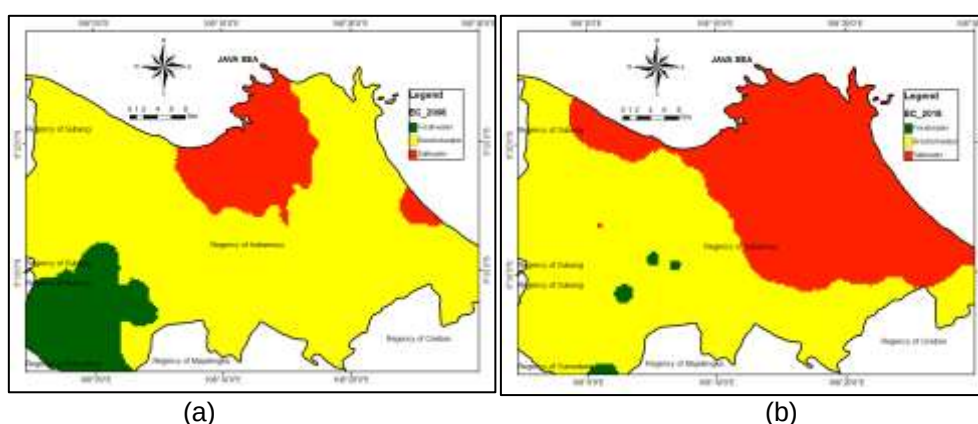


Figure 7. Spatial Distribution of EC.

Relationship Between Flood Exposure and Salinity

Statistical analysis shows a positive relationship between flood exposure and salinity indicators. Areas exposed to more frequent flooding generally exhibit higher EC and TDS concentrations, suggesting that repeated tidal inundation facilitates the transport of saltwater into irrigation networks and agricultural lands.

The correlation coefficient indicates that flood exposure is a significant factor influencing salinity conditions in the study area. This relationship can be explained by the direct interaction between coastal floodwaters and irrigation infrastructure, which allows seawater to penetrate inland through canals, drainage channels, and low-lying agricultural lands.

Furthermore, prolonged periods of inundation can increase salt accumulation in surface water bodies and agricultural lands. Repeated exposure to salty floodwaters can gradually increase background salinity levels, even after floodwaters recede.

These findings provide quantitative evidence supporting the hypothesis that coastal flooding not only functions as a hydrological hazard but also as a mechanism that accelerates saltwater intrusion and salinity development in irrigation systems.

Implications for Irrigation Resilience

A combined analysis of flooding and salinity reveals significant challenges to the long-term sustainability of coastal irrigation systems in Indramayu. Increasing salinity levels can reduce the suitability of irrigation water, decrease soil productivity, and negatively impact rice yields. Consequently, irrigation infrastructure in coastal areas must be evaluated not only in terms of water delivery performance but also in terms of its capacity to prevent saltwater intrusion.

The results indicate that traditional irrigation management approaches may become increasingly inadequate under future climate change. More frequent coastal flooding, combined with projected sea-level rise, will likely increase the risk of salinity and place additional pressure on agricultural production systems.

From a water resources management perspective, strengthening irrigation resilience requires an integrated strategy that simultaneously addresses flood control and water quality protection. Such an approach is particularly important in major rice-producing regions where agricultural productivity is closely linked to irrigation reliability and water quality. The findings of this study demonstrate the need to incorporate flood exposure assessments into irrigation planning and operational practices. By understanding the spatial interactions between coastal flooding and salinity intrusion, irrigation

managers can develop more effective adaptation measures to protect agricultural production and enhance the resilience of coastal agricultural systems.

ADAPTATION STRATEGIES

Based on the study findings, a comprehensive adaptation framework is proposed that combines better drainage management, optimization of tidal control structures, regular water quality monitoring, integration of flood risk and salinity information into irrigation planning, and climate change-resilient irrigation management practices, as shown in **Figure 8**.



Figure 8. Comprehensive Adaptation Framework.

Implementation of these measures can significantly increase the resilience of irrigation systems and support sustainable agricultural production in coastal environments experiencing increasing flood and salinity stress.

CONCLUSIONS

This study evaluates the risk of flooding-induced salinity within the coastal irrigation system of Indramayu Regency through the integration of flood inundation modeling and irrigation water quality assessment. Flood simulation results indicate that coastal irrigation areas are highly vulnerable to tidal inundation, especially under extreme tidal conditions and future sea-level rise scenarios. The inundation area increases substantially with coastal sea level rise, exposing agricultural land and irrigation infrastructure to greater flood hazards.

Water quality analysis revealed elevated concentrations of Electrical Conductivity (EC) and Total Dissolved Solids (TDS) in several locations, particularly near the coastline and estuarine systems. The spatial distribution of salinity indicators showed a strong correlation with flood-prone zones identified through inundation modeling.

Furthermore, statistical analysis demonstrated a positive relationship between flood exposure and salinity levels, indicating that recurring coastal flooding significantly contributes to the transport of saltwater into irrigation canals and agricultural land. These findings confirm that coastal flooding acts not only as a hydrological hazard but also as a major driver of irrigation water quality degradation and salinity development.

This study highlights the need for an integrated management approach that simultaneously addresses flood mitigation and salinity control. Adaptation measures such as improving drainage, optimizing tidal control structures, enhancing water quality monitoring, and incorporating flood risk information into irrigation planning are crucial for strengthening the resilience of irrigation systems in coastal agricultural areas. Overall, the proposed framework provides a practical and applicable approach to assessing salinity risks from flooding in coastal irrigation systems and can support decision-making in other delta and lowland agricultural regions facing similar environmental challenges.

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