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Determinants of Flow Connectivity in Small-Scale Wetland Irrigation Networks: A Sensitivity Analysis Approach In Aceh Jaya

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Abstrack

This study aims to analyze the determinants of flow connectivity in small-scale irrigation networks within wetland ecosystems of Aceh Jaya Regency, based on the perceptions of 135 water users. Five primary parameters were evaluated: channel structural stability (X_1), channel conveyance condition (X_2), sedimentation (X_3), flow connectivity (X_4), and discharge control performance (X_5). Integration of Spearman correlation, ordinal logistic regression, Sobol' sensitivity analysis, and cluster analysis reveals that canal conveyance condition (X_2) performs best. Channel structural stability (X_1) shows the lowest performance as a direct impact of wetland characteristics. Unstable soil conditions exacerbate the physical stability of irrigation networks in the region.Correlation findings reveal that cross-sectional stability is significantly and positively related to connectivity (r=0.452), while discharge control performance (X_5) shows a negative correlation (r=-0.513). A reverse causality phenomenon is indicated in locations with high water distribution constraints, where control infrastructure tends to be concentrated. Regression analysis confirms that good cross-sectional stability increases the probability of optimal connectivity by up to 2.6 times. Sensitivity analysis results identify flow control as the most critical parameter (S_{Ti}=0.51), followed by cross-sectional stability (S_{Ti}=0.44). This research recommends priority interventions in strengthening control infrastructure and cross-sectional stability adaptive to wetland hydrological dynamics based on a farmer cluster approach.

Keywords: *Small-scale Irrigation Networks, Flow Connectivity, Wetlands, Sobol' Sensitivity Analysis*

Abstrak

Penelitian ini bertujuan menganalisis determinan konektivitas aliran pada jaringan irigasi skala kecil di lahan basah Kabupaten Aceh Jaya berdasarkan persepsi 135 petani. Lima parameter utama dievaluasi meliputi stabilitas penampang (X_1), kebersihan saluran (X_2), sedimentasi (X_3), konektivitas aliran (X_4), dan pengendalian aliran (X_5). Melalui integrasi korelasi Spearman, regresi logistik, sensitivitas Sobol', dan analisis klaster, ditemukan bahwa kebersihan saluran (X_2) berkinerja terbaik, sedangkan stabilitas penampang (X_1) terlemah akibat kondisi tanah lahan basah yang labil. Hasil korelasi menunjukkan X_1 berhubungan positif signifikan dengan X_4 (r=0,452), sementara X_5 berkorelasi negatif (r=-0,513), mengindikasikan fenomena kausalitas terbalik pada area dengan kendala distribusi air tinggi. Analisis regresi mengonfirmasi bahwa peningkatan kondisi X_1 meningkatkan peluang konektivitas aliran (X_4) hingga 2,6 kali lipat. Analisis sensitivitas menempatkan pengendalian aliran (X_5) sebagai parameter paling kritis (S_{Ti}=0,51), diikuti

X_1 (S_{Ti}=0,44). Penelitian ini merekomendasikan prioritas intervensi pada infrastruktur pengendalian dan stabilisasi penampang yang adaptif terhadap dinamika hidrologi lahan basah berbasis pendekatan klaster petani.

Kata kunci: Jaringan Irigasi Kecil, Konektivitas Aliran, Lahan Basah, Sensitivitas Sobol'

1. Introduction

Irrigation networks play a fundamental role in sustaining agricultural productivity in wetland areas (Tucker et al., 2023) Small-scale irrigation systems in many regions operate under limited infrastructure capacity, where flow connectivity determines the effectiveness of water distribution across the network. Disruptions in connectivity can reduce conveyance efficiency and increase water losses. Infrastructure deterioration and sediment accumulation frequently weaken hydraulic performance (Fauzi et al., 2020). These conditions create uncertainty in determining priority interventions within irrigation schemes.

Small-scale irrigation networks in Aceh Jaya Regency operate under limited structural capacity and traditional management systems (Zahara, 2020). Agricultural productivity in the region remains closely linked to irrigation performance. Despite the relatively high annual rainfall reported by BMKG (2025), water availability does not necessarily guarantee reliable distribution across irrigation service areas. BPS (2025) indicates that the effective utilization of irrigated land is influenced no only by the availability of water resources but also by the functional condition of irrigation infrastructure and the quality of operational management. Therefore, irrigation erformance evaluation must consider technical reliability, equity of distribution, and water use efficiency as recommended by FAO (1999). According to the Government of Indonesia (2014), irrigation schemes with service areas of less than 500 hectares fall under the administrative authority of district governments, a governance arrangement that shapes maintenance strategies and the prioritization of infrastructure interventions. Furthermore, Burt and Styles (2001) stated if spatial positioning between upstream, middle, and downstream sections affects water distribution equity in traditional canal systems.

Several previous studies have evaluated irrigation performance using physical condition indices and service coverage indicators (FAO, 1999). In Indonesia, irrigation infrastructure assessments have often applied composite scoring approaches to evaluate system conditions. However, existing approaches frequently treat irrigation components as independent units and rarely examine hydraulic connectivity within irrigation networks as an integrated flow system. As a result, the relative influence of different parameters affecting irrigation performance remains insufficiently quantified.

Sensitivity analysis provides a quantitative framework to identify variables that significantly influence system performance (Saltelli et al., 2008). This approach enables a systematic evaluation of how variations in key parameters affect hydraulic connectivity within irrigation networks. However, the application of connectivity-based sensitivity analysis for small-scale wetland irrigation systems at the district level remains limited, particularly in regions managed under decentralized irrigation governance structures.

Therefore, the main research problem addressed in this study is how hydraulic connectivity factors influence the performance of small-scale irrigation networks in Aceh Jaya Regency and which parameters have the greatest impact on the effectiveness of water distribution.

2. Methodology

2.1 Study Area

This study was conducted in small-scale wetland irrigation networks located in Aceh Jaya Regency, Aceh Province, Indonesia, geographically situated between 4°22′–4°55′ North Latitude and 95°02′–95°34′ East Longitude. The region consists mainly of lowland and coastal plains influenced by tidal dynamics and seasonal rainfall, where agriculture relies on gravity-based irrigation through primary, secondary, and tertiary canals. Despite high rainfall, irrigation supply remains unreliable due to uneven distribution and limited canal storage. Intense rainfall events generate surface runoff that often causes seasonal flooding, particularly in lowland areas near rivers and wetlands, potentially disrupting canal hydraulic performance and water distribution continuity. These contrasting hydrological conditions provide a suitable context for analyzing irrigation flow connectivity. Figure 1 illustrates the spatial distribution of the observed irrigation networks and their relative position within the regency.

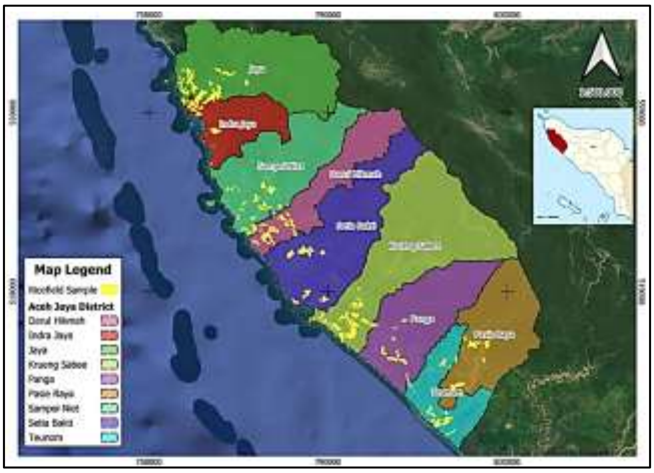

Figure 1 Distribution of irrigation performance evaluation samples for Aceh Jaya Regency in 2025 base map adopted from Zahara (2020).

The irrigation schemes operate under district authority and serve agricultural areas characterized by relatively flat topography. Water distribution is conveyed through open canals regulated by manually operated control structures. However, sediment deposition and vegetation growth frequently reduce hydraulic capacity and disrupt flow continuity between upstream and downstream service areas.

Table 1 summarizes the distribution of rice field areas and the dominant supplemental irrigation strategies across sub-districts in Aceh Jaya Regency. Most sub-districts are characterized by relatively large agricultural extents, with dominant cultivated areas generally exceeding 80 ha. However, the table reveals substantial variation in the sources of irrigation water used to support rice cultivation.

Table 1 Dominant Irrigated Area and Irrigation Water Supply Strategy

Sub distric	Actual Rice Field Area (ha)	Dominant expanse area (ha)	Primary Supplemental Irrigation Strategy (%)		
			Pumping and free intake/River	Creak/Swamp	Rainfed Area
Teunom	1.793,00	> 80,01	22,98	9,82	67,20
Krueng Sabee	1.677,00	> 80,01	20,89	14,82	64,29
Setia Bhakti	1.634,00	20,01 - <80,0	62,00	22,21	15,79
Sampoiniet	1.233,00	> 80,01	25,95	22,91	51,14
Jaya	2.000,00	> 80,01	49,00	29,22	21,78
Panga	1.605,00	> 80,01	50,47	17,81	31,72
Indra Jaya	800,00	> 80,01	49,00	11,43	39,57
Darul Hikmah	800,00	> 80,01	37,50	18,92	43,58
Pasie Raya	1.400,00	> 80,01	9,86	7,32	82,82

These spatial differences in irrigation support capacity provided the basis for selecting representative study sites. The study locations were determined through purposive sampling using predefined criteria (Dai et al., 2024). The primary criterion was the presence of productive paddy fields situated in wetland areas and riverbanks that utilize natural hydrological depressions as supplemental water sources. Selected land parcels have maintained continuous cropping since 2018 and are supported by active Water Users Associations (P3A) with access to relatively stable water sources rather than relying solely on rainfed conditions.

Within these traditional irrigation systems characterized by earthen canal networks, respondents were selected using Proportional Stratified Random Sampling to capture spatial variation in water distribution. The assessment framework followed the service zoning concept proposed by Burt and Styles (2001), where each subdistrict was divided into three hydraulic service zones: head, middle, and tail sections (Goel et al., 2021). The head section represents areas located near the primary water source or wetland, the middle section represents transitional distribution areas, and the tail section represents locations most vulnerable to water shortage risk.

A total of 15 respondents were selected in each subdistrict, with five respondents representing each service zone to ensure balanced spatial representation. The respondents were active rice farmers aged over 30 years who consistently cultivate their fields during both the wet (*rendeng*) and dry (*gadu*) cropping seasons. They are also regularly involved in collective canal maintenance through community-based cooperation, including sediment removal and minor repairs of earthen canals. Their long-term engagement in field operations and participatory irrigation management provides practical knowledge of seasonal water availability, canal flow conditions, and operational constraints within the irrigation network. In total, the study involved 135 respondents distributed across nine subdistricts in Aceh Jaya Regency.

The sample size was determined based on the principle of data saturation, which prioritizes informational depth over numerical magnitude. Saltelli et al. (2008) note that in environmentally and socioeconomically homogeneous populations, critical system-related information is typically captured within a range of 12–15 respondents, a conclusion also supported by Dai et al.(2024). Furthermore, the Rapid Appraisal Process (RAP) framework developed by FAO (1999) emphasizes spatial representativeness in small-scale irrigation assessments, prioritizing hydraulic positioning along canal networks rather than large population coverage to obtain a technically reliable evaluation of water distribution performance.

2.2 Rapid Appraisal Method

The Rapid Appraisal Method (RAM) is a participatory rapid assessment instrument designed to evaluate irrigation system performance through the integration of field-based technical data and water user perceptions (Chauhan & Ram, 2023).Unlike conventional evaluations that rely heavily on long-term secondary datasets, RAM enables direct identification of operational and physical constraints through structured observation and in-depth farmer interviews.

The application of RAM in this study focused on assessing the functional performance of self-managed irrigation systems located in wetlands and riverbank areas. The observed systems are dominated by earthen canals without permanent hydraulic structures. Performance evaluation therefore emphasized water supply reliability and distribution equity among farmers located in head, middle, and tail sections (Ferreira et al., 2023). RAM was considered appropriate for areas with high climatic variability such as Aceh Jaya Regency, as it captures farmer responses to dry spells and flood inundation within a short assessment period.

The technical indicators applied in this RAM framework were systematically derived from the parameters proposed by Praveen et al. (2025), ensuring methodological consistency and theoretical grounding. These indicators included: water source adequacy and reliability, earthen canal condition, distribution equity, and system dependency and adaptive capacity. Water adequacy and reliability assessed discharge stability from rivers, wetlands, or small reservoirs during critical crop growth stages (Lampayan et al., 2015). Canal condition evaluation examined sediment accumulation, wall seepage, and vegetation obstruction affecting conveyance capacity. Equity assessment measured water availability consistency at tail-end plots relative to head-end plots. System dependency and adaptation analysis evaluated the ability of the irrigation system to mitigate crop failure risk under extreme rainfall variability.

Data analysis combined quantitative scoring and qualitative interpretation to determine the irrigation performance index for earthen canal systems. The analysis emphasized physical stability and conveyance efficiency due to the non-permanent nature of the infrastructure. RAM-derived data were processed using a structured scoring technique and followed by an assessment of inter-variable relationships among technical indicators.

2.3 Research Parameters and Instruments

Five main parameters (X) were used as indicators of the physical and operational performance of the canal system, defined as follows:

1. Channel Structural Stability (X_1): The structural integrity of canal embankment geometry in relation to the risk of slope failure and bed erosion.
2. Channel Conveyance Condition (X_2): The degree of flow obstruction caused by vegetation accumulation (weeds) and organic debris within the channel.
3. Sedimentation (X_3): The rate of bed aggradation that reduces storage capacity and operational discharge of the canal.
4. Flow Connectivity (X_4): The continuity of water distribution from the upstream

source to the most downstream (tail-end) paddy plots.

5. Discharge Control Performance (X_5): The availability and functionality of discharge regulation structures, including traditional or temporary control devices, in managing water distribution.

The research instrument consisted of a structured questionnaire developed based on the performance indicators described above. The measurement scale employed a three-level ordinal scale: poor (−1), moderate or neutral (0), and good (1). This scale corresponds to the rapid appraisal scale commonly applied in participatory irrigation assessment. Tucker, B., et al. (2023) state, the selection of this scale was grounded in three considerations: clarity for respondents with diverse educational backgrounds, field survey efficiency, and the ability to clearly differentiate performance conditions into distinct categories.

Prior to implementation, the instrument underwent content validity testing through expert judgment involving two irrigation specialists and one field practitioner. Reliability testing was conducted on 30 respondents outside the main sample using the Cronbach’s Alpha coefficient to assess internal consistency. The parameters serving as research indicators are presented in Table 2.

Table 2 Evaluation Parameters for Irrigation System Performance

Parameter	Perational Definition	Operational Definition
Channel Structural Stability	The integrity of earthen canal banks and embankments in maintaining geometric form and hydraulic function.	– Embankments intact with no slope failure obstructing flow (1)
		– Minor cracks or small slope failures present without affecting flow (0)
		– Embankments collapsed or leveled with surrounding land, with major cracks or slope failures disrupting flow (−1)
Channel Conveyance Condition	The extent of vegetation growth and aquatic plants that impede water conveyance.	– Unobstructed canal flow (1)
		– Presence of weeds without significant flow obstruction (0)
		– Canal heavily overgrown with weeds or shrubs, water appears stagnant (−1)
Sedimentation	The thickness of sediment deposits on the canal bed that reduce conveyance capacity.	– Canal bed free from significant sediment deposits (>10 cm) (1)
		– Sediment present but not yet reducing discharge capacity (0)
		– Shallow canal bed due to sediment accumulation, resulting in reduced flow capacity (−1)
Flow Connectivity	The continuity of water delivery from the upstream source to the most downstream service plot.	– Water reaches the most downstream plot without interruption (1)
		– Water reaches the downstream plot with significantly reduced discharge (0)
		– Flow interrupted midway due to leakage or obstruction (−1)
Discharge Control Performance	The availability and operational performance of emergency or permanent discharge control structures.	– Functional discharge control structure available (1)
		– Control structure available but operating suboptimally (0)
		– No control structure available, resulting in uncontrolled overflow (−1)

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2.4 Method of Data Analysis

Data analysis employed an integrative approach combining descriptive statistics, association testing, and Sobol'-based sensitivity analysis to identify the parameters that most strongly influence flow connectivity (X_4). The Sobol' method was selected due to its ability to decompose the total output variance into individual parameter contributions and interaction effects among input variables (Saltelli et al., 2008).

The first stage involved descriptive statistical analysis to characterize respondent evaluations across the five parameters. Ordinal data scaled at −1, 0, and 1 were transformed into frequency distributions, total scores, and mean values to identify the highest- and lowest-performing parameters. Spearman's rank correlation analysis was then applied to examine bivariate relationships among variables. A 5×5 correlation matrix was constructed to detect statistically significant associations at $\alpha = 0.05$ and $\alpha = 0.01$. Particular attention was given to the correlations between X_1, X_2, X_3, and X_5 in relation to X_4.

The subsequent stage involved cross-tabulation analysis to explore relational patterns between parameters with strong theoretical linkage. Emphasis was placed on examining the interaction between X_1 and X_4 as well as between X_5 and X_4. Statistical significance of the observed associations was tested using the Chi-Square (χ^2) test. The strength of association between variables was measured using the contingency coefficient (C), which quantifies the degree of relationship within categorical data distributions (Coolidge, 2012):

$$C = \sqrt{\frac{\chi^2}{\chi^2+n}} \qquad (1)$$

In this study, ordinal logistic regression was simultaneously applied to examine the effects of X_1, X_2, X_3, and X_5 on flow connectivity (X_4) as the dependent variable. The cumulative logit model was formulated as (Sobol′, 2001):

$$logit[P(X_4 \leq j)] = \alpha_j - (\beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_5 X_5) \qquad (2)$$

where α_j represents the threshold parameter for category j, and β_i denotes the regression coefficients of the respective independent variables. Model adequacy was evaluated using Nagelkerke's Pseudo R^2 to assess explanatory strength. Sensitivity analysis was subsequently performed using the Sobol' method, approximated through variance decomposition based on ANOVA principles. The analytical procedure consisted of the following steps (Sobol′, 2001) :

1. The total variance of the dependent variable (X4) was calculated as:

$$Var\ Y = \frac{\sum_i^n (Y_i - \bar{Y})^2}{n-1} \qquad (3)$$

2. The conditional variance for each input parameter (Xi) was computed as:

$$Var[E(Y|X_i)] = \frac{\sum_{k=1}^{m} n_k (\overline{Y_k} - \bar{Y})^2}{n-1} \qquad (4)$$

3. The first-order sensitivity index (Si) was then determined as:

$$S_i = \frac{Var[E(Y|X_i)]}{Var(Y)} \qquad (5)$$

Si > 0,3 (highly sensitive);
0,1 < Si ≤ 0,3 (moderately sensitive),
Si ≤ 0,1 (low sensitivity),

4. The total-order sensitivity index (STi) was approximated as:

$$S_{Ti} \approx 1 - \frac{Var[E(Y|X_{\sim i})]}{Var(Y)} \tag{6}$$

The first-order sensitivity index represents the direct contribution of parameter X_i to the variance of flow connectivity X_4. The total-order index quantifies the overall contribution of X_i including all higher-order interaction effects with other parameters. An interaction effect was considered significant when S_{Ti} - S_i > 0,1 (Wainwright et al., 2014).

Cluster analysis was conducted using the two-step clustering method. This procedure identified homogeneous response patterns among respondents based on the five performance parameters. The clustering results were used to group respondents and detect anomalous cases, such as those exhibiting poor structural stability (X_1) but good flow connectivity (X_4).

3. Results And Discussion

3.1 Parameter Correlation Analysis

This section presents the results of a structured survey conducted among 135 irrigation water users to assess the performance of the irrigation network across five core parameters (X_1–X_5). The analysis describes respondents' evaluations of the system's structural condition and operational performance based on the predefined assessment criteria. Table 3 provides the distribution of ratings assigned to each parameter.

Table 3 Distribution of Respondent Ratings

Parameter	Score -1 (Poor)	Score 0 (Moderate)	Skor 1 (Good)	Total Score	Average
X_1	77 (57,0%)	10 (7,4%)	48 (35,6%)	-29	-0,215
X_2	46 (34,1%)	10 (7,4%)	79 (58,5%)	33	0,244
X_3	58 (43,0%)	14 (10,4%)	63 (46,7%)	5	0,037
X_4	66 (48,9%)	8 (5,9%)	61 (45,2%)	-5	-0,037
X_5	50 (37,0%)	8 (5,9%)	77 (57,0%)	27	0,200

The data presented in Table 3 revealed a marked variation in performance across the evaluated parameters. X_2 (channel conveyance condition) demonstrated the strongest performance, as evidenced by the highest aggregate score (+33) and a dominant proportion of favorable ratings (58.5%), indicating relatively well-maintained flow paths. In contrast, X_1 (channel structural stability) exhibited the lowest performance, reflected in a negative total score (−29) and a majority of respondents (57.0%) assigning poor ratings, suggesting prevalent structural deficiencies within the earthen canal sections.

Table 4 Spearman Correlation Matrix of Performance Parameters

Parameter	X_1	X_2	X_3	X_4	X_5
X_1	1,000				
X_2	-0,124	1,000			
X_3	0,318**	0,412**	1,000		
X_4	0,452**	-0,186*	-0,089	1,000	
X_5	-0,281**	0,539**	0,218*	-0,513**	1,000

noted: ** indicates significance at α=0,01; * indicates significance at α=0,05

To further examine the structural pattern of relationships among these parameters, a Spearman rank correlation analysis was subsequently performed to assess their bivariate associations. The complete correlation matrix, including corresponding levels of statistical significance, was presented in Table 4.

The analysis revealed a positive and significant correlation between X_1 and X_4 ($r = 0.452$; $p < 0.01$), indicating that higher embankment stability promotes better flow connectivity. In contrast, X_5 exhibited a significant negative correlation with X_4 ($r = -0.513$; $p < 0.01$), suggesting that the presence of flow control structures is associated with reduced connectivity. These findings likely reflect endogeneity, as flow control installations are typically concentrated in locations already experiencing connectivity problems. This implies that improving embankment stability may be more effective in enhancing connectivity than merely adding flow control devices, highlighting the need for targeted infrastructure planning in irrigation networks.

The cross-tabulation analysis between X_1 and X_4 revealed a significant association ($\chi^2 = 28{,}47$; $p<0{,}001$) with a contingency coefficient (C) of 0,417. The results indicate that when X_1 is poor, the majority of respondents (66.2%) experienced poor connectivity. Whereas when X_1 is good and most respondents (64.6%) reported good connectivity. This pattern aligns with open-channel hydraulics theory, which emphasizes that cross-sectional stability plays a crucial role in maintaining continuous flow.

Analysis of the cross-tabulation between X_5 and X_4 confirms the negative association identified in the correlation analysis. At locations with poor flow control, 74.0% of respondents reported good connectivity. Whereas at locations with good flow control, 70.1% of respondents experienced poor connectivity. This pattern reinforces the possibility of reverse causality, as flow control interventions are often implemented in channel segments that already exhibit connectivity issues.

To examine the combined influence of all parameters on flow connectivity, an ordinal logistic regression was performed with X_4 as the dependent variable and X_1, X_2, X_3, and X_5 as predictors. This approach was chosen because ordinal logistic regression can handle a dependent variable with three ordinal categories (-1, 0, 1) while simultaneously assessing the effects of multiple independent variables ((Dai et al., 2024). Beyond the scope of correlation analysis, which measures only bivariate relationships, ordinal logistic regression allows identification of predictors that remain significant after controlling for the contributions of other variables. The estimation results are presented in Table 5.

Table 5 Ordinal Logistic Regression Results with X_4 as the Dependent Variable

Variabel	Coefisien (β)	Wald	Sig.	Exp(β)
X_1	0,942	18,234	0,000	2,565
X_2	-0,184	0,892	0,345	0,832
X_3	-0,376	3,456	0,063	0,687
X_5	-1,103	21,456	0,000	0,332

Nagelkerke Pseudo $R^2 = 0{,}387$

he model indicates a strong positive effect of X_1 on X_4 ($\mathrm{Exp}(\beta) = 2.565$; $p < 0.001$). This suggests that improvements in X_1 significantly raise the odds of X_4

being in a higher connectivity category. In contrast, X_5 shows a significant negative effect (Exp(β) = 0.332; $p < 0.001$). This indicates that an increase in flow control reduces the likelihood of higher connectivity. X_3 exhibits a marginally significant negative effect ($p = 0.063$), while X_2 does not have a significant impact. Overall, the regression model explains 38.7% of the variance in X_4, highlighting the relative importance of structural stability over flow control interventions.

A cluster analysis was conducted to uncover more nuanced response patterns at the respondent level. A total of 135 respondents were grouped based on the similarity of their evaluations across the five parameters, yielding five distinct clusters with unique profiles. Cluster A, representing 25.9% of respondents, is characterized by uniformly poor ratings for all physical parameters (X_1, X_2, X_3, and X_5), while connectivity (X_4) was nonetheless reported as good. Cluster B (15.6% of respondents) displays good stability and connectivity, even though the remaining parameters were rated poorly. Cluster C, the largest cluster (33.3% of respondents), exhibits both poor stability and poor connectivity despite favorable ratings for other parameters. Cluster D (14.8% of respondents) reflects optimal conditions, with all parameters evaluated as good. Cluster E (10.4% of respondents) represents a transitional group, with multiple parameters receiving intermediate ratings. This variation highlights the heterogeneous and complex nature of the irrigation network, underscoring the need for differentiated management strategies, which will be elaborated in the discussion section. This statement was also expressed by Kativhu, S. M. K., & Moyo, M. M. (2020).

3.2 Quantitative Sensitivity Analysis of Connectivity Using Sobol’ Indices

Global sensitivity analysis was applied to quantify the contribution of input variables to variations (Sobol′, 2001) in irrigation flow connectivity. Sensitivity analysis is widely used in environmental and hydrological modeling to evaluate how uncertainty in model inputs influences system outputs and to identify influential parameters (Amarasinghe et al., 2021). In this study, the variance-based Sobol’ method was employed to decompose output variance into contributions from individual parameters and their interaction effects (Sobol′, 2001). This approach is widely adopted in water resources and environmental modeling(Dai et al., 2024) because it effectively captures nonlinear relationships and parameter interactions (Saltelli et al., 2008). Based on this approach, a sensitivity analysis was conducted to quantify the contribution of each parameter to the variability in irrigation connectivity. The results presented as first-order sensitivity indices (S_i) and total sensitivity indices (S_{Ti}) (Tabel 6).

Table 6 Sensitivity Indices of Parameters on Connectivity (X_4)

Parameter	First-Order Sensitivity Index (S_i)	Total-Order Sensitivity Index (S_{Ti})	Interaction Contribution
X_1	0,322	0,440	0,118
X_2	0,047	0,150	0,103
X_3	0,02	0,100	0,080
X_5	0,382	0,510	0,128

Varians Total X_4 = 0,892

The sensitivity analysis reveals that X_5 is the most influential parameter, with a direct contribution of 38.2% and a total contribution of 51% to the variability in X_4, indicating that flow control plays a critical role in determining connectivity. X_1 ranks second, contributing 32.2% directly and 44% in total, highlighting the importance of cross-sectional stability in maintaining continuous flow. Although X_2 and X_3 have relatively small direct effects, their significant interaction contributions ($S_{Ti} - S_i > 0.1$ for X_2 and approximately 0.1 for X_3) suggest that these parameters exert their influence primarily through interactions with other factors. These findings imply that improving connectivity requires not only attention to the most sensitive parameters (X_5 and X_1) but also a consideration of the combined effects of less dominant parameters to address complex network dynamics effectively.

3.3 Respondent Cluster Patterns – Implications for Irrigation Performance

The cluster analysis identified five distinct respondent groups, reflecting the heterogeneity of field conditions. Cluster C (33.3% of respondents) exhibited poor cross-sectional stability (X_1) and connectivity (X_4) despite favorable ratings for other parameters, corroborating the regression results (Expβ = 2.565). When channel stability is compromised, water is lost before reaching downstream plots, and other parameters cannot compensate, consistent with hydraulics principles emphasizing channel geometry integrity (M. G. Bos et al., 2005; Syifa & Permana, 2024).

Cluster D (14.8%) represents ideal conditions, with all parameters rated as good, serving as a benchmark for effective management. Cluster B (15.6%) shows that robust stability can maintain connectivity even when other parameters are weak. Cluster E (10.4%) is a transitional group with multiple intermediate ratings, indicating conditions near the threshold of system degradation.

Cluster A (25.9%) presents an anomaly: all physical parameters (X_1, X_2, X_3, X_5) were rated poorly, yet connectivity (X_4) was reported as good. This highlights the model's limitation in explaining connectivity variability (Nagelkerke R^2 = 0.387, 61.3% unexplained). Possible explanations include topography (steep slopes), excessive upstream discharge, or alternative downstream water sources allowing perceived adequate service despite technical interruptions (Goel et al., 2021).

3.4 Implications for Policy and Irrigation Management

The insights derived from the respondent group analysis, ordinal logistic regression, and Sobol' sensitivity assessment collectively provide a robust empirical foundation for guiding irrigation management and policy decisions. The observed heterogeneity among respondent groups highlights that connectivity is not solely determined by individual parameters, but by their interactions and the structural context of each segment. Regression results demonstrated the critical role of X_1 in maintaining connectivity, while sensitivity analysis identified X_5 and X_1 as the most influential parameters affecting network performance (Rahmadani et al., 2024). These indicated that interventions cannot follow a uniform approach; instead, they must be strategically prioritized and tailored to the specific vulnerabilities and strengths identified in each group, ensuring that limited resources are allocated where they can yield the greatest improvement in connectivity and system resilience

For X_5, the negative regression effect (Exp $\beta = 0.332$) suggests the presence of reverse causality, indicating that segments with pre-existing connectivity issues tend to receive flow control interventions. Consequently, management actions should focus on evaluating and rehabilitating existing structures rather than constructing new ones indiscriminately (Goel et al., 2021). In contrast, X_1 can be addressed more directly through earthen canal repairs using locally available materials, complemented by active farmer participation to foster ownership, sustainability, and long-term maintenance (M. G. Bos et al., 2005).

The heterogeneity of respondent groups further underscores the need for tailored intervention strategies. Group C (33.3%) with poor stability and connectivity requires immediate structural rehabilitation. Group A (25.9%), exhibiting anomalous patterns, warrants further investigation before interventions are applied. Group D (14.8%) represents optimal conditions and should be reinforced as a benchmark for best practices. Group E (10.4%), a transitional group, requires preventive measures to prevent further degradation, while Group B (15.6%), with robust stability, can be maintained through routine maintenance and monitoring (Rahmadani et al., 2024).

X_2, which achieved the highest total score, reflects the effectiveness of collective maintenance practices conducted by farmer organizations (P3A). Strengthening institutional capacity and providing incentives for consistently active groups can help sustain this positive performance over time (Fereres & Soriano, 2006; Mohd Yusof Hj Abdullah et al., 2012). Sedimentation (X_3), although exhibiting lower sensitivity, can serve as an early warning indicator, signaling the onset of system degradation before connectivity is significantly impacted.

Moreover, the adoption of information technology offers substantial opportunities for predictive, data-driven irrigation management. Implementation of simple SMS-based notifications or lightweight applications, synchronized with operator data, can provide farmers with timely information on irrigation schedules, water allocations, and operational issues. Such systems enhance responsiveness, support adaptive management, and improve overall network efficiency, particularly in regions with limited digital infrastructure (Faurès & Santini, 2008).

4. Conclusions and Recommendations

4.1 Conclusions

This study investigated the determinants of flow connectivity in small-scale wetland irrigation networks (<200 ha) in Aceh Jaya. The analysis combined farmers’ field perceptions with statistical evaluation and global sensitivity analysis. The results indicate that channel structural stability, defined as the integrity of canal embankments and bed geometry against slope failure and erosion, is a primary determinant of irrigation flow connectivity. Stable canal sections maintain the hydraulic capacity required to sustain hydraulic flow continuity along the irrigation network. The findings also identify the importance of discharge control performance, referring to the availability and functionality of flow regulation structures that manage water distribution within the canal system. Poorly functioning or improperly operated control structures can disrupt flow regulation and reduce water delivery reliability between upstream and downstream service areas.

The analysis further shows that channel conveyance condition is affected by vegetation growth, debris accumulation, and sediment deposition within the canal. These factors gradually reduce canal storage and conveyance capacity and influence irrigation connectivity mainly through their interaction with structural stability and discharge regulation. Overall, irrigation connectivity in small-scale systems depends on the combined performance of canal structural stability and effective discharge regulation. Improving connectivity therefore requires targeted interventions focusing on canal stabilization, rehabilitation of discharge control structures, and routine maintenance to control vegetation growth and sediment accumulation. Strengthening these measures through participatory farmer involvement can enhance water distribution reliability and support more resilient irrigation management in wetland-based irrigation networks.

4.2 Recommendations

Intervention strategies should be tailored to the characteristics of each respondent cluster rather than applied uniformly. Future research is recommended to expand the scope of variables by incorporating additional factors that may influence flow connectivity, such as actual water discharge, channel slope, distance from upstream, farmer participation, and institutional support from P3A. Using a more detailed measurement scale, for example a 5-point Likert scale, would allow finer differentiation of conditions and improve the sensitivity of the analysis.

Future studies are recommended to conduct repeated measurements over time to capture the temporal dynamics of network degradation and rehabilitation and to evaluate the effectiveness of interventions. Sensitivity analysis results should also be validated using hydraulic simulation models to provide more accurate estimates of parameter influence. In addition, a focused mixed-methods investigation of Cluster A is particularly important to identify compensatory mechanisms underlying the observed anomalous connectivity patterns, ensuring that interventions are based on a comprehensive understanding of system behavior over time.

Finally, disseminating research outcomes to relevant stakeholders in Aceh Jaya is essential to ensure that insights are translated into practical irrigation management and planning, supporting sustainable improvements across the irrigation network.

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