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Original Research Article

Priority Zoning of Paddy Field Dam for Recovery-based Planning within Land Improvement District of the Shin-Tone River Basin, Japan

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ABSTRACT

Paddy field dams support both agricultural production and flood mitigation. However, their recovery after dam functionality, particularly within Land Improvement District-managed areas, has not been sufficiently studied. This study develops a hierarchical priority-zoning framework to guide recovery-based management in the Shin-Tonegawa Land Improvement District, Japan. Three key indicators – the actual drainage flow distance to the main drainage channel, the actual drainage flow distance to the final drainage point, and the potential storage volume – were calculated for individual paddy field plots and aggregated dam units. These indicators were then analysed using hierarchical clustering, decision-tree modelling, and analysis of variance to identify classes and assess the relative influence of each indicator. The findings show that hydraulic accessibility is the primary driver of recovery priority at both spatial scales. The plot-level results indicate that fields near the main drainage channel and outlet point can be drained quickly. At the dam level, downstream dams near the outfall must be prioritized to restore trunk-channel capacity and prevent upstream congestion. By integrating these two perspectives, this study proposes a nested recovery framework in which dam-level prioritization structures system restoration, followed by plot-level triage within prioritized dams.

KEYWORDS

Dam function recovery, Rainwater storage, Agricultural resilience, Hydraulic connectivity, Drainage network, Hierarchical clustering.

INTRODUCTION

Paddy field dams (PFDs) in Japan serve as multifunctional components of agricultural water management systems, supporting both crop production and flood mitigation [1]. Historically, paddy fields have served as temporary water-retention areas during heavy rainfall. Previous studies have demonstrated their contributions to flood-risk reduction [2], peak discharge attenuation [3], ecological conservation through support of wetland communities [4], residential flood damage mitigation [5], and watershed-scale flood mitigation [6]. In recent

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decades, this role has been formalized through the development of PFDs that incorporate controlled inlet and outlet structures to regulate water levels. These engineered controls enhance floodwater retention capacity while maintaining agricultural production [7]. The implementation and management of PFDs are closely linked to the institutional framework of Land Improvement Districts (LIDs), the cooperative organizations established under Japan's Land Improvement Act. LIDs are responsible for the coordinated management of irrigation infrastructure and water distribution systems across agricultural areas [8]. Their long-term effectiveness has been attributed to farmer-based collective governance and fair water allocation mechanisms, which contribute to the sustainability of irrigation districts [9]. Within LID-managed areas, PFDs operate as part of a broader networked water management system, which includes artificial agricultural drainage channels, main drainage channels, and drainage pumping. For example, during heavy rainfall events, LIDs can implement operational strategies, such as temporary water storage within PFDs and regulated discharge through drainage channels afterward, thereby enhancing the overall resilience of agricultural zones.

Flood events in Japan, often triggered by extreme rainfall, severely disrupt agricultural systems, particularly in low-lying paddy-field zones [10]. PFDs play a vital role in this context as they are designed to retain excess rainfall temporarily. Field observations have demonstrated the rainfall storage function of low-lying paddy areas equipped with controlled outlets [11]. The flood mitigation effect of PFDs has been quantified in agricultural watersheds in Japan [12]. Their contribution to sustainable flood resilience has also been demonstrated in urbanizing catchments [13]. Comparative assessments have shown that PFDs can serve as an effective nature-based alternative to conventional flood mitigation measures [14]. The broader technical principles and applications of PFDs as flood-control measures have also been well documented [15]. Their potential for implementation in basin-scale flood management has recently been evaluated under contemporary agricultural conditions [16]. Project-based assessments have further confirmed their capacity to reduce flood peaks and downstream runoff volumes [17]. However, their retention function also leaves substantial volumes of standing water in agricultural plots after events, delaying field operability and crop replanting. Post-disaster assessment following the Great East Japan Earthquake and Tsunami documented the broad challenges associated with agricultural reconstruction, including damage to farmland and water management infrastructure [18]. Investigations in Miyagi Prefecture further identified soil degradation and salinity impacts as major barriers to restoring agricultural production [19]. Institutional recovery programs demonstrated the importance of coordinated reclamation efforts for rehabilitating tsunami-affected farmland [20]. The persistence of salinity damage and impaired drainage facilities was shown to delay farmland recovery even after inundation had receded [21]. Evaluations of restored farmlands indicated that soil fertility recovery remained a critical factor influencing the resumption of agricultural activities [22]. In addition, reconstruction projects for agricultural production highlighted the need for long-term coordination among farmers, researchers, and government agencies to fully restore agricultural productivity [23]. Similarly, recovery assessments following Typhoon Hagibis demonstrated that the restoration of drainage and water-management infrastructure is a critical determinant of post-flood recovery efficiency [24]. Evaluation of irrigation reservoirs as flood adaptation measures further showed that hydraulic storage and operational management strongly influence the effectiveness of flood mitigation and recovery action [25]. Their findings underscored the need for prioritization frameworks that consider hydraulic connectivity and operational constraints when planning post-flood interventions. Without a structured recovery plan, water removal is reactive and inefficient, leading to prolonged inundation.

The priority zoning of PFDs is essential for accelerating post-event recovery in agricultural landscapes, particularly in well-managed zones under LID governance. Water retention measures are recognized as important climate adaptation strategies as they intentionally store excess water within the landscape following heavy rainfall events [26]. However, efficient drainage and recovery require operational prioritization, as optimization studies have shown that drainage infrastructure must be managed strategically to minimize waterlogging losses in paddy fields [27]. Evaluations of smart paddy field dam systems have further demonstrated that flood mitigation performance depends on coordinated water-level management within interconnected drainage networks [28]. Consequently, clearing all inundation plots simultaneously is often impractical within hierarchical drainage systems. In this study, priority zoning addresses this operational limitation by ranking PFDs based on objective indicators, including the actual drainage flow distance to the main drainage channel, actual drainage flow distance to the final drainage point, and potential storage volume. The drainage distance to the main drainage channel reflects the accessibility of each field to the primary conveyance system, whereas the drainage distance to the final outlet captures the field's position within the broader network. Potential storage volume also influences recovery by affecting recovery duration, but its impact seems to be conditional on hydraulic connectivity. Based on these relationships, this study hypothesizes that hydraulic accessibility is the primary determinant of recovery prioritization, with storage volume playing a subordinate role. This assumption is grounded in operational realities, which emphasize that the rate of water removal is constrained more by drainage connectivity than by retention depth [29].

Previous studies on paddy field dams (PFDs) have primarily focused on their flood-mitigation and water-retention functions [1], demonstrating that PFDs can reduce runoff, attenuate peak discharge, and contribute to flood resilience through temporary water storage in agricultural landscapes. Similarly, studies on Land Improvement Districts (LIDs) have emphasized their roles in coordinating irrigation, drainage, and water management infrastructure [8]. Despite these advances, knowledge gaps remain. First, existing PFD studies largely focus on the flood-event phase, evaluating storage performance and downstream flood reduction, whereas the post-event recovery phase has received considerably less attention. Second, recovery studies have mainly examined infrastructure damage, soil conditions, and institutional responses, but rarely investigate how the spatial structure of drainage networks influences recovery sequencing and efficiency. Third, although LIDs possess centralized operational control over irrigation and drainage systems, their management capabilities have not been systematically translated into decision-support frameworks for recovery prioritization. Consequently, there is limited theoretical understanding of how hydraulic connectivity, network position, and drainage accessibility interact to determine recovery performance at multiple spatial scales. This limitation restricts the ability of water managers to prioritize interventions and optimize resource allocation following major rainfall events.

To address these gaps, this study hypothesizes that recovery priority in LID-managed agricultural landscapes is primarily governed by drainage-network accessibility, whereby paddy field plots and dam units with shorter actual drainage flow distances to major drainage channels and final outlets exhibit higher recovery potential. The hypothesis was tested using the Shin-Tonegawa Land Improvement District-managed agricultural zone in the downstream section of the Shin-Tone River Basin, Japan. Key indicators were quantified at both the paddy field plot and dam scales and used to classify recovery priorities through a hierarchical zoning framework. By integrating these classifications into a nested recovery-planning model, the study provides a systematic methodology for prioritizing post-flood recovery actions, contributing beyond the development of a site-specific management tool. The study advances understanding of distance-driven recovery processes in managed agricultural drainage systems and proposes a transferable methodology for linking hydraulic connectivity with recovery prioritization across multiple spatial scales. The Shin-Tonegawa LID therefore serves as a case study for testing a broader recovery-planning framework that can be adapted to other managed agricultural landscapes with hierarchical drainage networks.

This study was conducted in a low-lying agricultural zone located in the downstream section of the Shin-Tone River Basin within the Kanto Plain, eastern Japan (Figure 1). The area is managed by the Shin-Tonegawa Land Improvement District (https://sintonegawa.or.jp/), which operates an integrated irrigation and drainage system for agricultural water management.

The landscape is predominantly composed of paddy fields and is characterized by relatively flat topography and low elevation. The agricultural water management system consists of irrigation supply channels, agricultural drainage channels, main drainage channels, and pumping stations. Paddy field plots are connected to artificial agricultural drainage channels, which convey excess water to the main drainage channel. Water is subsequently discharged through pumping facilities to the basin outlet. This hierarchical drainage network forms the basis for water regulation and drainage management within the study area.

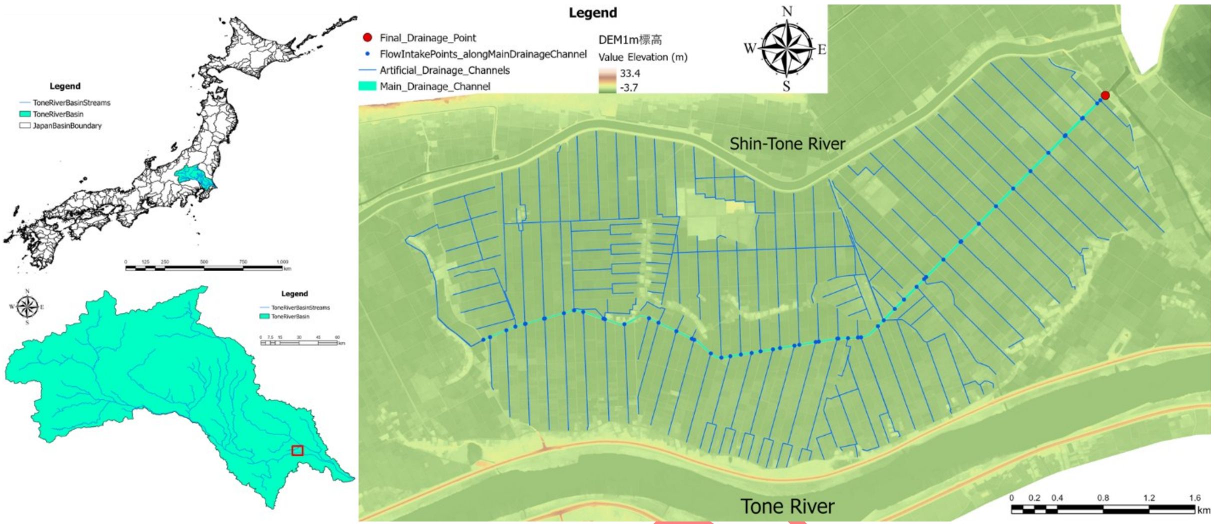

Figure 1. Case study

MATERIALS AND METHODS

The section describes the dataset used and the methodological framework adopted. First, a summary of the data sources and their respective applications was provided. Subsequently, the analytical procedures and methods employed to achieve the study objective were detailed, including the data analysis and evaluation approaches used throughout the study.

Data Used

Three primary geospatial datasets were used to support the priority zoning framework of PFDs for recovery-based planning within the Shin-Tonegawa LID (Table 1). A high-resolution 1m Digital Elevation Model (DEM) from the Geospatial Information Authority of Japan (GSI) provided detailed elevation data critical for estimating water storage capacity. The elevation differences within each paddy field plot were used to derive the potential storage depth and volume. The fine spatial resolution ensured an accurate representation of the microtopographic variations that influenced water retention. Polygon data for the paddy field plots were obtained from the Ministry of Agriculture, Forestry, and Fisheries of Japan (MAFF). These boundaries served as fundamental spatial units for plot-level analysis, enabling the calculation of plot areas, linkage with DEM data, and connectivity assessment with the drainage network. Plot-level data were aggregated into dam units, forming the basis for multi-spatial units and zoning analysis. A waterline map from the GSI delineated the main drainage channel and the artificial agricultural drainage channels managed by the LID system. This polyline dataset supported the calculation of the actual drainage flow distance from each paddy field plot to the main drainage channel and final drainage point. Using this drainage network, a flow navigation approach was applied to trace the water conveyance paths and estimate realistic drainage distances. Together, these datasets provide a comprehensive representation of the topography and infrastructure that governs water movement and storage. Their integration in ArcGIS Pro 3.6 enabled precise spatial analysis, supporting the development of a hierarchical zoning framework for the recovery-based planning of PFDs.

Table 1. Summary of the data used

Data type	Specification	Source
Digital Elevation Model	1m resolution raster data	Geospatial Information Authority of Japan (https://service.gsi.go.jp/kiban/app/)
Paddy Field Plots	Polygon data	Ministry of Agriculture, Forestry and Fisheries of Japan (https://www.maff.go.jp/j/tokei/porigon/hudeporidl.html)
Waterline	Polyline data	Geospatial Information Authority of Japan (https://service.gsi.go.jp/kiban/app/)

Analytical Flow

An analytical framework was developed to establish priority zoning of PFDs within the Shin-Tonegawa LID, considering recovery-based planning for post-event management. The workflow integrates GIS-based spatial analysis and statistical classification to determine hierarchical priorities at two scales: individual paddy field plots and aggregated dam units. The overall framework is illustrated in Figure 2.

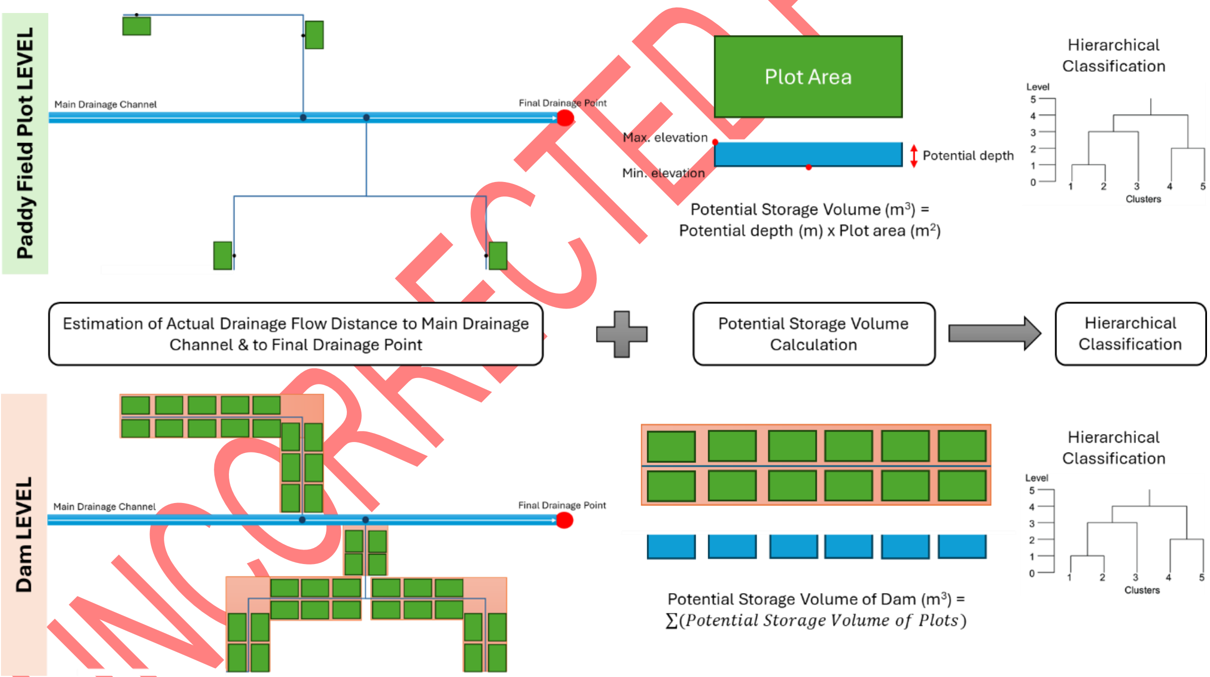

Figure 2. Analytical framework

Paddy field plot level analysis. At the paddy field plot level, the actual drainage flow distance to the main drainage channel was calculated using a flow navigation approach along an artificial agricultural drainage network. Initially, the *Near* analysis tool in ArcGIS Pro 3.6 was applied to identify intersection points between paddy field polygons and artificial drainage channel polylines, representing the nearest connection of each plot to its corresponding channel. Subsequently, the *Split Line at Points* function was employed to segment the artificial drainage channels at these intersection points, enabling the computation of the split length associated with each plot. The cumulative lengths of these segmented channels were summed to derive the actual drainage-flow distance from each plot to the main drainage channel.

To determine the actual drainage flow distance to the final drainage point, the analysis incorporated the distance between the intake point of each artificial drainage channel into the main drainage channel and the outlet of the latter. The total actual drainage flow distance for each plot was obtained by adding the plot-to-main channel distance and the main drainage channel segment length to the outlet.

The potential storage volume of each paddy field plot was estimated using Equation (1).

$$Potential\ Storage\ Volume\ (m^3) = Potential\ Depth\ (m)\ \times Plot\ Area\ (m^2) \quad (1)$$

where the potential depth was calculated as the difference between the maximum and minimum elevation values within each plot derived from the 1m DEM, as shown in Equation (2):

$$\begin{aligned} &Potential\ Depth\ (m) \\ &= Maximum\ Elevation\ (m) - Minimum\ Elevation\ (m) \end{aligned} \quad (2)$$

Dam level analysis. At the dam level, the paddy field plots connected to the same artificial agricultural drainage channel were aggregated into dam units. The actual drainage flow distance from each dam to the main drainage channel was calculated as the mean of the corresponding actual drainage flow distances to the main drainage channel for all constituent paddy field plots within the dam. Similarly, the actual drainage flow distance from each dam to the final drainage point was computed as the average of the paddy field plot-level actual drainage flow distances to the final drainage point within the dam. The potential storage volume for each dam was derived by summing the estimated storage volumes of all paddy field plots within the dam unit.

Hierarchical classification and statistical analysis. Following the computation of indicators for both spatial levels (Table 2), priority zoning was conducted using a hierarchical classification at the paddy field plot and dam scales. Classification at these two levels was essential to capture both the microscale and system-scale dynamics of post-event recovery within the LID. At the paddy field plot level, recovery decisions typically occur at the operational unit of individual paddy fields, where factors such as drainage accessibility and storage capacity directly influence the time required to restore agricultural functionality. Classifying plots enables managers to identify fields that can be cleared first, thus ensuring a rapid re-entry into cultivation. Conversely, at the dam level, recovery planning must account for the collective behaviour of plots connected to the same artificial drainage channel and flow intake point into the main drainage channel. These dams function as subnetworks within the LID drainage system. Classifying dams allows managers to prioritize entire lateral systems for intervention and optimize resource allocation.

Table 2. Indicators at both spatial levels

Spatial Level	Indicators	Unit
Paddy field plot level	Actual drainage flow distance to main drainage channel	m
	Actual drainage flow distance to final drainage point	m
	Potential storage volume	m^3
Dam level	Actual drainage flow distance to main drainage channel	m
	Actual drainage flow distance to final drainage point	m
	Potential storage volume	m^3

Prior to classification, all indicators were standardized using a z-score transformation to remove scale effects. No log-transformation was applied because the objective was to preserve the original relationships among indicators, while standardization ensured equal weighting in the clustering procedure. Hierarchical clustering was then applied using Ward's minimum variance method in JMP Student Edition 19, which minimizes within-cluster dispersion and produces compact and interpretable groupings. The dendrogram and cluster history guided the selection of cluster numbers at each level, balancing simplicity and separation. The cluster assignments were subsequently treated as categorical labels for interpretation and operational zoning. To convert the clusters into actionable decision rules, a decision tree analysis was performed using the partition function in JMP Student Edition 19, with cluster ID as the target and standardized indicators as predictors. The resulting tree identified the variable splits and threshold values that best explained the cluster structure. Finally, an Analysis of Variance (ANOVA) was conducted in JMP Student Edition 19 using the Fit Model function with Standard Least Squares to test the statistical distinctiveness of clusters across indicators. F-ratios, p-values, and model R^2 confirmed significant differences among cluster means and quantified effect sizes. A summary of the classification and statistical analyses is presented in Table 3.

Table 3. Summary of classification and statistical analysis

Analytical steps	**Analytical method**	**Software**
Hierarchical clustering analysis	Ward method	JMP Student Edition 19
Decision tree analysis	Partition function with the Decision Tree method	JMP Student Edition 19
ANOVA test	Fit Model function with the Standard Least Squares personality	JMP Student Edition 19

RESULTS

Given that this study employed a two-scale analytical framework, the results were presented separately according to the spatial scales considered. The findings were divided into paddy field plot-level outcomes and dam-level outcomes. This distinction enabled a comprehensive evaluation of the characteristics of paddy field dams from both the individual plot perspective and the aggregated dam-unit perspective.

Paddy Field Plot Level Outcomes

At the paddy field plot level, hierarchical clustering produced a dendrogram showing a clear separation into three classes. A detailed classification of the paddy field plots is shown in Figure 3 and presented in Table 4. Class 1 included 1,449 plots characterized by short actual drainage flow distances, averaging 399.16m to the main drainage channel and 2,695.48m to the final drainage point, combined with a high mean storage volume of 1,544.56 m^3. These plots were concentrated near the main drainage channel and final drainage point, offering favourable conditions for rapid water removal and early recovery. Class 2, the largest group with 1,568 plots, exhibited moderate mean actual drainage flow distances of 800.37m to the main drainage channel and 5,308.84m to the final drainage point, and the lowest average storage volume of 705.23 m^3. Typically located in the mid-zone laterals, these plots face drainage delays despite their low retention capacities, representing an intermediate recovery priority. Class 3 comprised 491 plots with long mean actual drainage flow distances of 2,231.21m to the main drainage channel and 6,063.62m to the final drainage point, and a mean storage volume of 1,414.49 m^3. Situated in remote laterals on the network periphery, these plots require extended coordination, making them the lowest priority for immediate recovery.

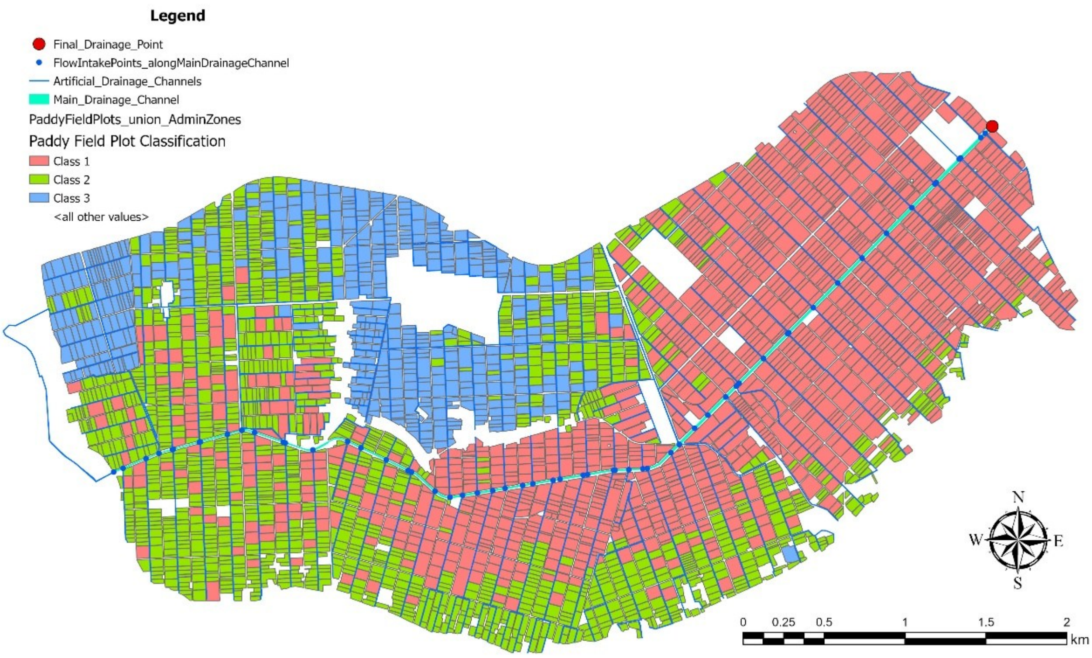

Figure 3. Classification map at the paddy field plot level

Table 4. Classification results at the paddy field plot level

Hierarchical Classification	Count of Paddy Field Plots	MEAN Actual Drainage Flow Distance to the Main Drainage Channel [m]	MEAN Actual Drainage Flow Distance to the Final Drainage Point [m]	MEAN Potential Storage Volume [m^3]
Class 1	1,449	399.16	2,695.48	1,544.56
Class 2	1,568	800.37	5,308.84	705.23
Class 3	491	2,231.21	6,063.62	1,414.49

The decision tree for the plot-level classification generated interpretable rules for operational zoning (Figure 4). The first split was based on the actual drainage flow distance to the main drainage channel, confirming its dominant influence on recovery prioritization. Subsequent splits incorporated the actual drainage flow distance to the final drainage point and the potential storage volume, refining the classification of plots with similar accessibility. These rules support the hypothesis that hydraulic accessibility is a stronger determinant of recovery speed than storage capacity.

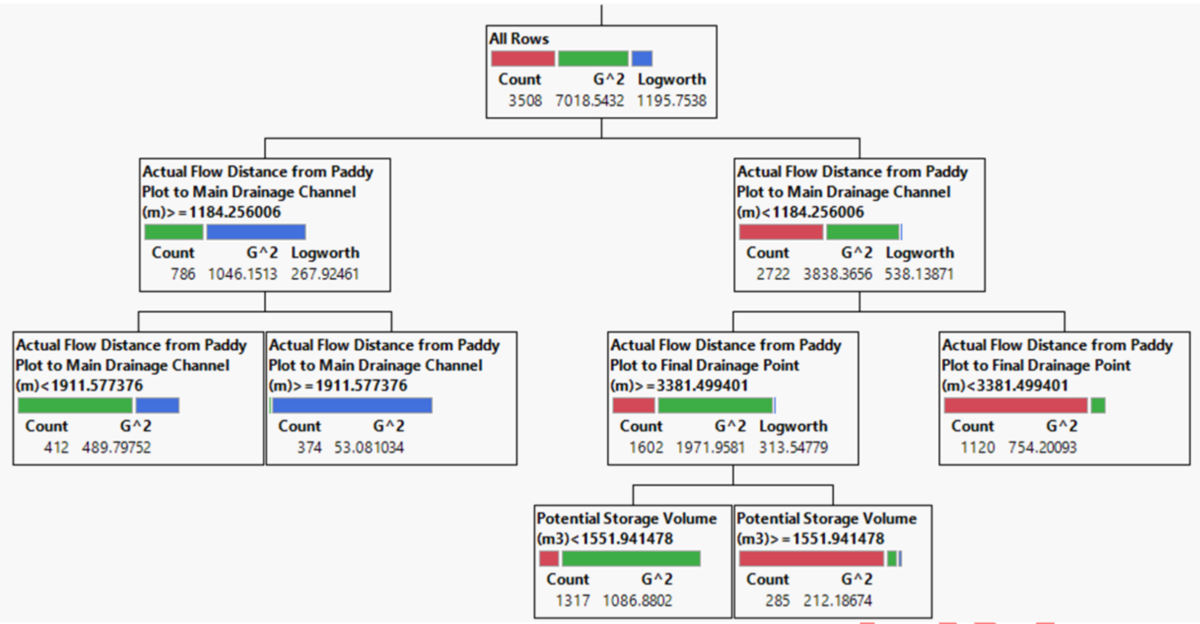

Figure 4. Decision tree of the paddy field plot-level classification

The ANOVA results (Table 5) confirmed the statistical distinctiveness of the clusters, showing highly significant differences across all indicators ($p < 0.0001$). The effect summary indicated that the actual drainage flow distance to the main drainage channel accounted for the largest variance ($R^2 = 0.6967$; F ratio = 4,024.7280), followed by the actual drainage flow distance to the final drainage point ($R^2 = 0.4670$; F ratio = 1,535.4050), and potential storage volume ($R^2 = 0.2322$; F ratio = 530.1257). These findings reinforce the idea that the conveyance distance is the primary determinant of recovery priority, whereas storage capacity plays a secondary role.

Table 5. Statistical test results at the paddy field plot level

Explanatory Variables	R^2	F Ratio	Prob > F
Actual drainage flow distance to the main drainage channel	0.6967	4,024.7280	< 0.0001
Actual drainage flow distance to the final drainage point	0.4670	1,535.4050	< 0.0001
Potential storage volume	0.2322	530.1257	< 0.0001

Dam Level Outcomes

At the dam level, hierarchical clustering produced a dendrogram showing a clear separation into four classes. A detailed classification of the dam units is shown in Figure 5 and Table 6. Class 1 included 62 dams with moderate actual drainage flow distances, averaging 778.65 m to the main drainage channel and 3,854.45 m to the final drainage point, and a mean storage capacity of 19,231.13 m^3. These dams occupy mid-network positions, offer balanced recovery conditions, and form manageable priority groups for early to intermediate intervention. Class 2, comprising 38 dams, had a short mean actual drainage flow distance to the main drainage channel of 469.37 m but a long mean actual drainage flow distance to the final drainage point of 6,025.78 m, with a moderate mean storage volume of 22,497.31 m^3. Located in upstream laterals, these dams connect quickly to the main drainage channel but require extended downstream conveyance, making them suitable for staged interventions. Class 3 consisted of 24 dams with a short mean actual drainage flow distance to the final drainage point of 1,694.55 m, a moderate mean actual drainage flow distance to the main drainage channel of 520.68 m, and the largest mean storage capacity of 54,621.21 m^3. Positioned near the outfall, these dams enable rapid clearance despite their high retention volumes and serve as strategic storage hubs for accelerated recovery. Class 4, with 38 dams, was defined by a long actual drainage flow distance to both the main drainage channel of 2,232.53m and the final drainage point of 6,302.41m, combined with the lowest mean storage capacity of 17,901.07 m^3. Located at the network periphery, these dams require extended coordination, making them the lowest priority for immediate recovery and candidates for deferred intervention.

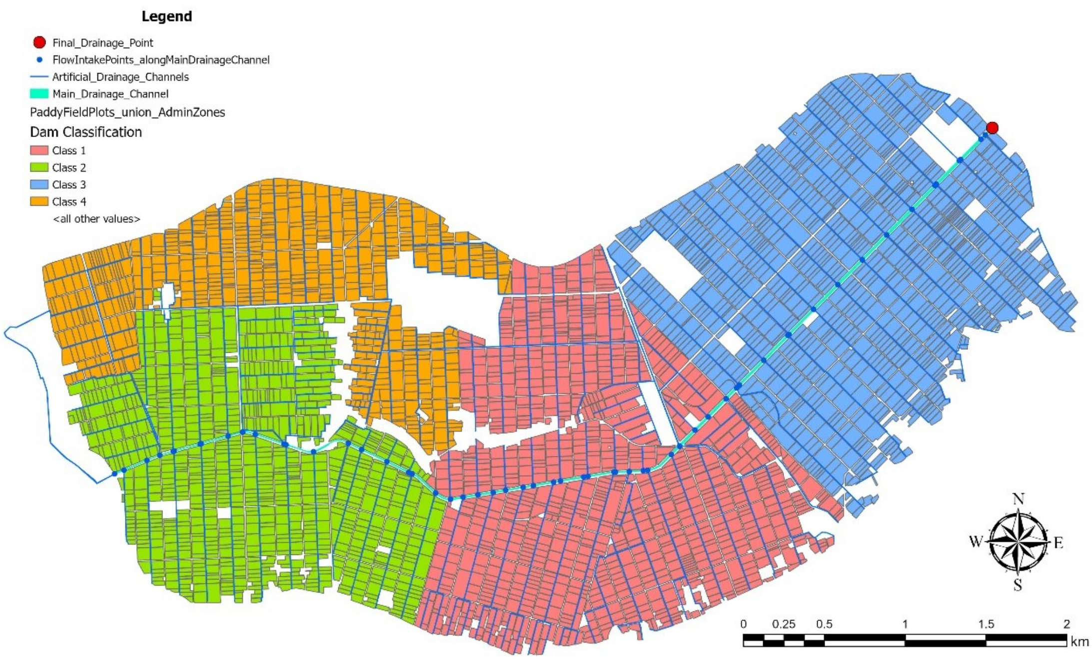

Figure 5. Classification map at the dam level

Table 6. Classification results at the dam level

Hierarchical Classification	**Count of Dams**	**MEAN Actual Drainage Flow Distance to the Main Drainage Channel [m]**	**MEAN Actual Drainage Flow Distance to the Final Drainage Point [m]**	**MEAN Potential Storage Volume [m^3]**
Class 1	62	778.65	3,854.45	19,231.13
Class 2	38	469.37	6,025.78	22,497.31
Class 3	24	520.68	1,694.55	54,621.21
Class 4	38	2,232.53	6,302.41	17,901.07

As shown in Figure 6, the dam-level decision tree confirmed that the actual drainage flow distance to the final drainage point was the primary determinant of the classification, followed by the actual drainage flow distance to the main drainage channel and the potential storage volume. This hierarchy highlights the critical role of the network positions in system-scale recovery planning. The resulting splits provide actionable rules for sequencing dam interventions, supporting a dam recovery strategy that maximizes hydraulic efficiency.

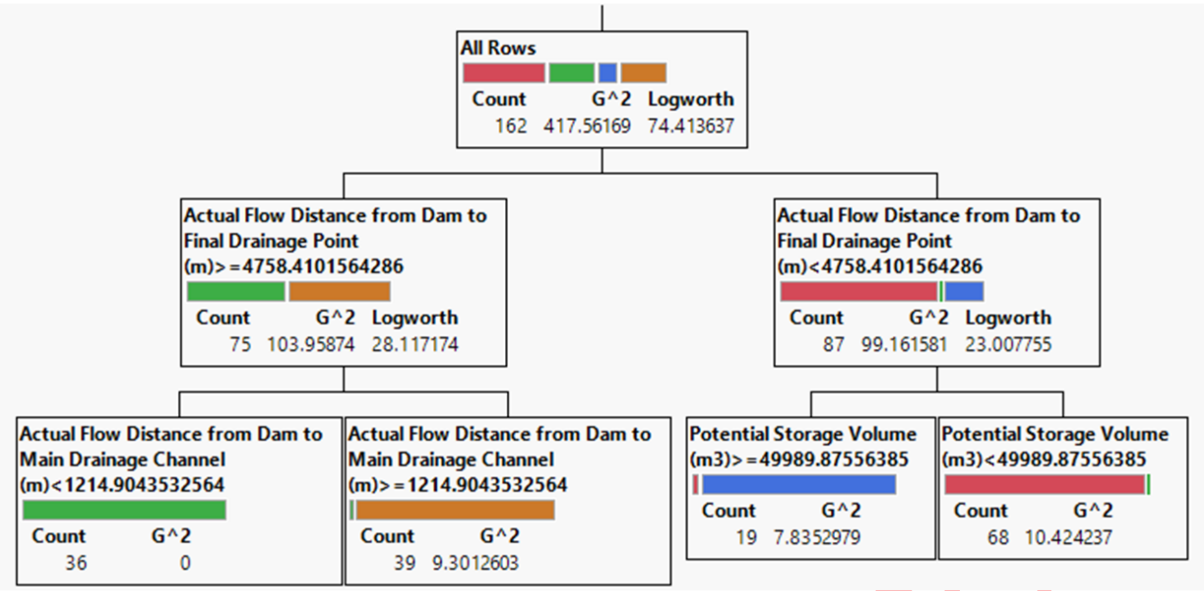

Figure 6. Decision tree of the dam-level classification

The ANOVA results (Table 7) confirmed the statistical distinctiveness of the dam-level classes, with all indicators showing highly significant differences ($p < 0.0001$). The effect summary revealed that the actual drainage flow distance to the main drainage channel ($R^2 = 0.7372$; F ratio = 147.7163) and the actual drainage flow distance to the final drainage point ($R^2 = 0.7193$; F ratio = 134.9645) explained most of the variance, whereas the potential storage volume ($R^2 = 0.5499$; F ratio = 64.3395) also contributed substantially. These findings reinforce the idea that conveyance distances dominate recovery prioritization at the dam level, with storage capacity serving as a critical secondary factor for strategic retention planning.

Table 7. Statistical test results at the dam level

Explanatory Variables	R^2	F Ratio	Prob > F
Actual drainage flow distance to the main drainage channel	0.7372	147.7163	< 0.0001
Actual drainage flow distance to the final drainage point	0.7193	134.9645	< 0.0001
Potential storage volume	0.5499	64.3395	< 0.0001

DISCUSSION

Based on the study's findings, the discussion was structured around the two spatial scales examined, namely the paddy field plot level and the dam level. The implications of the results for recovery-based planning were discussed separately for each scale to highlight the recovery processes at that scale. Furthermore, an integrated plot-dam framework was proposed to support more effective recovery-based planning of paddy field dams by linking plot-scale characteristics with dam-scale management strategies. Finally, the limitations of the study were discussed, providing directions for future studies and methodological improvement.

Recovery-based Planning at Paddy Field Plot Level

The classification of the paddy field plots provided critical insights into the conditions governing post-event recovery within the Shin-Tonegawa LID. The results demonstrated that hydraulic accessibility, expressed through the actual drainage flow distance to both the main drainage channel and the final outlet, is the dominant factor influencing recovery priority, whereas the potential storage volume functions as a secondary but complementary determinant. Plot-level classification provides a practical basis for field-scale recovery sequencing. As shown in Figure 7, plots in Class 1, which combine a short drainage flow distance with moderate storage capacity, should be prioritized for early intervention because they enable rapid clearance and timely resumption of farming activities. Class 2 plots represent intermediate recovery priorities, whereas Class 3 plots, characterized by long drainage distances and high storage volumes, are more suitable for deferred recovery or temporary retention strategies to prevent overloading of the drainage network.

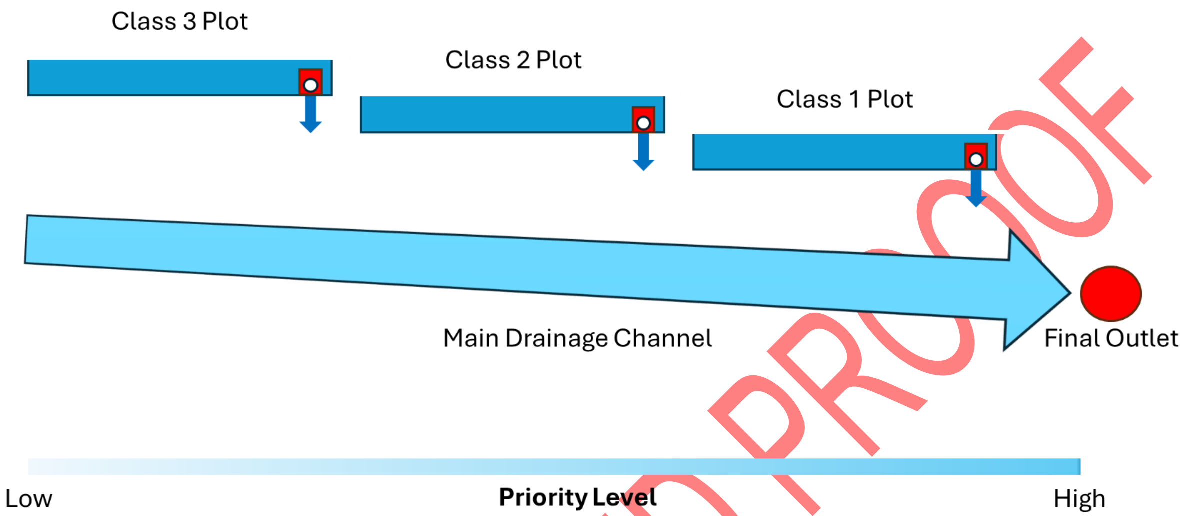

Figure 7. Priority zoning at the paddy field plot level for recovery-based planning

Plots located closest to the main drainage channel and final drainage point consistently fell into the highest-priority class. Their shorter conveyance paths facilitate faster discharge through drainage channels and pumping infrastructure, thus underscoring the operational importance of network proximity in recovery planning. These findings are consistent with those of broader studies on agricultural drainage hydraulics. Graph-theoretic routing analyses have shown that fields with shorter flow paths exert a greater influence on network performance because hydraulic attenuation accumulates along complex drainage networks [30]. Similarly, numerical analyses of pumping station hydraulics indicated that additional hydraulic structures increase energy losses [31], while structural configurations such as bends, valves, and pipes contribute significantly to frictional resistance [32]. The accessibility-based approach adopted in this study represents water movement through drainage-network connectivity and actual flow distances rather than through explicit simulation of hydraulic transport processes [33].

The influence of the drainage distance to the final outlet further highlights the role of the network position in determining recovery efficiency. Even plots relatively close to the main drainage channel may experience a delay if positioned upstream within the trunk system, where water removal is constrained by the downstream capacity. This finding reflects the system-scale hydraulic interdependencies documented in network modelling studies. Previous research has demonstrated that upstream nodes depend on the throughput capacity of downstream segments [34]. Likewise, bottlenecks in looped networks can be identified using network linearization approaches that characterize downstream constraints on upstream branches [35]. The effect of lateral alignment relative to flow direction on drainage performance has also been reported, emphasizing the importance of system-wide hydraulic connectivity rather than local proximity alone [36].

Although the potential storage volume was statistically significant, its influence was weaker than that of drainage distance. Plots with high storage volumes can prolong inundation if recovery is delayed; however, high-volume plots located near the main drainage channel can still be rapidly cleared owing to efficient hydraulic connectivity. This interaction suggests that the storage volume should act as a refinement variable rather than as a primary determinant. Similar conclusions have been reported in studies on farm water storage strategies, where storage capacity contributes most effectively to water resilience when combined with efficient conveyance systems [37]. These findings support the interpretation that retention capacity complements, rather than replaces, drainage accessibility. Furthermore, recent machine-learning studies have demonstrated that environmental processes are often governed by nonlinear interactions among multiple controlling factors, highlighting the value of interaction-based analyses beyond single-variable assessment [38]. Similar approaches may provide additional insight into the combined effects of storage volume, drainage accessibility, and hydraulic connectivity on recovery performance.

Recovery-based Planning at Dam Level

The classification of dam units within the Shin-Tonegawa LID provides a system-scale perspective on post-event recovery prioritization. While plot-level analysis focuses on the operability of individual fields, dam-level zoning captures the hydraulic connectivity and operational interdependencies of shared drainage laterals. As illustrated in Figure 8, dams located near the final outlet (Class 3) should be prioritized, followed by those with short lateral distances from the main drainage channel (Classes 1 and 2). Remote dams (Class 4), which are characterized by long conveyance paths, should be scheduled for deferred recovery or managed temporarily as retention areas. This sequencing ensures that gate control aligns with network hydraulics, reducing recovery time and minimizing the risk of secondary flooding.

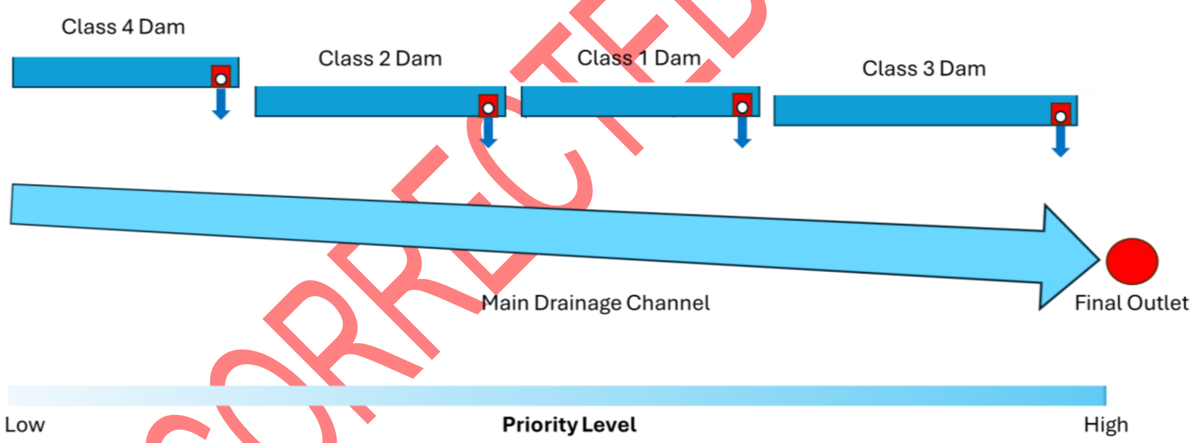

Figure 8. Priority zoning at the dam level for recovery-based planning

The study identified the actual drainage flow distance to the final outlet as the most influential determinant of the dam-level recovery priority. Dams situated near the basin outlet enable rapid water clearance, reduce backwater accumulation, and free trunk channel capacity for upstream conveyance. By contrast, dams located far from the final outlet require prolonged pumping cycles and can generate bottlenecks if addressed prematurely. This pattern underscores the need for network-aware recovery sequencing in which downstream units are cleared before upstream units. Similar findings have been reported in network flow optimization studies, which demonstrated that prioritizing downstream restoration maximizes overall system capacity [39] and improves the efficiency of post-disaster recovery operations [40].

The second key determinant is the actual drainage-flow distance to the main drainage channel, which represents the ease with which lateral flows connect to the trunk system. Dams with short lateral distances can rapidly discharge water once the trunk capacity becomes available, making them suitable for early recovery stages. Conversely, dams with long lateral distances experience delays, even after downstream clearance, reinforcing their classification as lower-priority zones. These results align with those of other studies, emphasizing the hydraulic importance of lateral connectivity. A study has shown that hydrological connectivity decreases substantially with increasing drainage distance [41], while integrated flow-management studies have emphasized the critical role of lateral connectivity in maintaining effective drainage performance [42]. Furthermore, proximity-based prioritization has been identified as an effective strategy for improving recovery and restoration outcomes within interconnected hydraulic networks [43].

Although storage volume plays a secondary role in drainage distance, its influence is more pronounced at the dam scale than at the individual paddy-field plot scale. Dams with exceptionally large storage capacities, particularly those located near outlet points, can function as strategic retention hubs during a staged recovery. These units can temporarily detain water to prevent overload within the system and then be cleared rapidly when the pumping resources are allocated. Similar observations have been reported in reservoir management studies, where large storage facilities located near outlet points were found to reduce peak discharge and provide buffering effects that enhance recovery performance [44]. Likewise, analyses conducted at broader spatial scales have suggested that reservoirs with substantial storage volumes located near critical hydraulic nodes contribute significantly to system capacity and downstream relief [45].

Proposed Recovery-based Planning of Integrated Plot-Dam Levels

The integration of plot- and dam-level classifications into a nested recovery planning framework represents a significant advancement in the post-event management of LID-managed paddy field zones. Although plot-level zoning provides fine-scale information on field operability, dam-level zoning captures the system-scale hydraulic constraints that dictate how the drainage network functions during recovery. The nested approach resolves scale mismatches by sequencing recovery interventions at the dam level, followed by plot-level triage within prioritized dams. Dam-level classification identifies the hydraulic nodes that are most critical for restoring the trunk channel capacity, specifically dams located near the final outlets that can be cleared rapidly. After these primary dams are addressed, plot-level zoning refines recovery actions by targeting fields with short lateral distances and moderate storage volumes, enabling quick clearance and an earlier return to cultivation. The value of hierarchical planning frameworks has been widely recognized in flood and water management studies. Multilevel prioritization approaches have been shown to reduce system-wide recovery delays by coordinating interventions across multiple spatial scales [46]. Similarly, studies of agricultural drainage systems in the Nile Delta have demonstrated that interactions among system-, intermediate-, and field-level processes are critical for effective drainage management, highlighting the importance of multi-scale decision-making in complex hydraulic networks [47]. These findings support the application of nested recovery planning as a practical strategy for improving operational efficiency and accelerating post-flood recovery in managed agricultural landscapes.

The integrated zoning framework provides a clear and structured roadmap for post-event recovery, as illustrated in Figure 9. Stage 1 prioritizes the dams near the final outlets to quickly restore the system's conveyance capacity. Stage 2 targets plots within dams with short lateral distances and moderate storage volumes, offering rapid operability gains. Stage 3 focuses on remote dams and high-volume plots, which may require deferred recovery or temporary retention strategies to prevent system overload. This staged approach ensures that recovery actions remain hydraulically efficient, reduce agricultural downtime, and strengthen overall resilience.

Figure 9. Integrated plot-dam levels priority zoning for recovery-based planning

This study advances distance-dominant recovery theory by demonstrating its applicability across spatial scales. Recent research has shown that recovery outcomes following flooding events can be quantified using spatially explicit recovery metrics, highlighting the importance of recovery pathways and accessibility [48]. Fundamental studies on watershed and drainage network structure have established that flow distance is a key factor governing hydrological connectivity and water movement [49]. Research on flood drainage rights has further emphasized the importance of efficient drainage allocation and downstream conveyance capacity in flood management systems [50]. In addition, investigations of multiscale water cycle processes in paddy field irrigation districts have demonstrated that drainage performance is strongly influenced by connectivity across multiple spatial scales [51]. At both the plot and dam levels, the actual drainage flow distances, first to the main drainage channel and then to the final drainage point, emerged as the primary determinants of recovery priority. The potential storage volume plays a secondary yet operationally important role in informing decisions regarding deferred recovery. By embedding these principles within a nested governance structure, this study introduced a new paradigm for post-event management in well-managed agricultural landscapes under LID administration, shifting the focus from conventional flood mitigation to maximizing post-event operability and recovery efficiency.

Limitations of the Study

This study has several limitations that should be considered when interpreting the findings or extending the proposed recovery-planning framework. First, the framework adopts an accessibility-based network approach in which recovery priority is determined primarily by actual drainage flow distances. Although the results demonstrate the utility of distance-based metrics for identifying recovery sequences, hydraulic capacity, pump operation, and transient flow dynamics were not incorporated. Second, the framework focuses on network structure and recovery accessibility and does not account for physical damage to agricultural infrastructure. Factors such as berm failure, sediment accumulation, land subsidence, and outlet deterioration may affect recovery performance and should be incorporated into future multi-criteria recovery assessment. Third, the framework was tested in a well-managed Land Improvement District characterized by a hierarchical drainage network and centralized water management. While the specific priority zones identified in this study are unique to the Shin-

Tonegawa system, the underlying methodological contribution is broader. The results provide evidence that recovery prioritization can be systematically derived from drainage-network accessibility and hydraulic connectivity across multiple spatial scales. Additional applications in different agricultural drainage systems, including multi-outlet networks, gravity-controlled systems, and regions with decentralized management structures, are needed to evaluate the generality and transferability of the proposed approach.

CONCLUSIONS

This study presents a novel priority zoning framework for paddy field dams that supports recovery-based planning in Land Improvement District-managed agricultural landscapes. Rather than focusing solely on flood mitigation or rainwater storage functions, the framework introduces recovery efficiency as a key criterion for post-flood agricultural management. By integrating high-resolution spatial data with network-based analysis at both plot and dam scales, the study demonstrated that drainage connectivity and actual flow distance are critical determinants of recovery performance, while storage capacity provides an important complementary function for retention planning.

The significance of this study lies in its shift from conventional flood-control perspectives toward a recovery-oriented approach that emphasizes how quickly agricultural systems can return to normal operation following flood events. This perspective is increasingly important as climate variability intensifies the frequency and duration of flood disturbances in managed agricultural landscapes. The proposed nested zoning framework provides a practical decision-support tool that can help Land Improvement Districts allocate resources, prioritize drainage operations, and reduce the economic impacts associated with prolonged inundation and delayed farming activities.

Beyond its practical application, the study contributes to the broader understanding of spatial recovery processes in agricultural drainage systems by highlighting the role of network position and hydraulic connectivity in determining post-event recovery priorities. The framework also establishes a foundation for integrating recovery considerations into adaptive water-management strategies and agricultural resilience planning. Future research should incorporate hydraulic simulations, pump operation constraints, and observed recovery timelines to further evaluate and refine the framework across different agricultural and hydrological settings.

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NOMENCLATURE

Abbreviations

ANOVA	Analysis of Variance
DEM	Digital Elevation Model
GSI	Geospatial Information Authority

LID Land Improvement District
MAFF Ministry of Agriculture, Forestry, and Fisheries
PFD Paddy Field Dam

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