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IDENTIFYING VEGETATION SUCCESSION SITES TO REPURPOSE AS STORAGE SPACES IN THE ALLUVIAL PLAIN OF THE LOWER TONE RIVER BASIN, JAPAN

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ABSTRACT

The loss of potential storage space due to vegetation succession is a significant issue, particularly in unmanaged farmlands connected to drainage channels, reducing the effectiveness of the land in mitigating flood risk. This study aimed to discover unmanaged spaces within the alluvial plain of the Lower Tone River Basin, Japan, that have undergone vegetation succession. By monitoring the distribution of vegetation succession, the aim was to develop a technical method to identify and repurpose vegetation succession sites as storage spaces through proposed interventions to mitigate inland flooding within the alluvial plain of the Lower Tone River Basin. The analytical framework involved extracting alluvial plain areas, monitoring vegetation succession by integrating optical and synthetic aperture radar satellite images over the 2017–2024 period, analyzing the relationship between land-use types and vegetation succession patterns, extracting targeted vegetation succession sites, and classifying targeted vegetation succession patches based on height above the nearest drainage, distance to the nearest drainage channel, and other parameters. The classification resulted in three functional classes. Class 1 spaces were closely linked to water channels, making them critical areas for immediate floodwater storage. Class 2 spaces served as intermediate storage areas, situated at moderate distances from the water channels. Class 3 spaces provided final storage spaces for dispersed floodwater at the highest elevation and the furthest distance from the drainage channels. The sequential impact of inland flooding characterizes the functional hierarchy among Classes 1, 2, and 3, considering the on-site conditions. Overflowing from the drainage channels first impacts the Class 1 spaces. As the floodwater dispersed, it reached Class 2 spaces. Finally, Class 3 spaces served as the last line of mitigation, storing floodwater spread widely across the landscape. By identifying and categorizing vegetation succession patches for conversion into storage spaces, this study provides a basis for prioritizing areas for intervention and developing targeted flood mitigation strategies.

Keywords: Vegetation mapping, Satellite images, Unmanaged spaces, Storage function, Lowland plain, Inland flooding

INTRODUCTION

Alluvial plains are extensive flatlands created by deposited sediment transported by rivers and are predominantly used for agricultural activities (Rajakumari *et al*., 2021). Due to their rich soil fertility (Butler, 2024), these plains are highly suitable for cultivation. In addition to their primary role in agricultural production, these farmlands also play a crucial role in flood control. In Japan, the Ministry of Land, Infrastructure, Transport, and Tourism implemented a river basin flood control policy that involves positioning and designating rice paddy fields along rivers into flood buffer zones. These areas are now used as flood-retarding basins and adjustment ponds within river management systems (Koike, 2021; Saha *et al*., 2023; Satoh, 2022). However, flooding in alluvial plains presents significant challenges because inland and external water flooding can occur. Inland water flooding is often exacerbated by surface runoff from the surrounding land use and overflow from drainage systems (Astuti *et al*., 2019; Fereshtehpour *et al*., 2025; Nilap *et al*., 2025). This runoff can overwhelm the agricultural drainage channels and cause localized flooding. Moreover, external water flooding occurs when rivers overflow their banks, inundating the surrounding alluvial plains (Cui *et al.,* 2024; Eccles *et al*., 2019). One of the critical concerns in alluvial plains is the potential loss of the floodwater storage function against inland flooding. Agricultural land and drainage channels are often designed as retarding basins to store and manage external flood water from rivers (Ishikawa & Akoh, 2023). However, when these areas are subjected to inland flooding, their capacity to store additional floodwater is compromised. Therefore, the increased risk of inland flooding from agricultural drainage channels is a significant concern.

Dispersed storage spaces within alluvial plains are vital components of nature-based solutions (NbS) (Griffiths *et al*., 2024; Hartmann *et al*., 2019; Penning *et al*., 2023), which aim to mitigate the risk of inland flooding, particularly from drainage channels. These storage spaces, including wetlands, act as natural buffers that absorb and temporarily store excess water during heavy rainfall or when drainage channels overflow. For example, Finna (2023) provided a mini-review discussing the multifaceted role of natural wetlands in flood mitigation and water storage, emphasizing their importance in maintaining a balanced ecosystem and enhancing resilience to extreme weather events. Additionally, Ferreira *et al*. (2023) provided an overview of how natural and constructed wetlands regulate hydrological fluxes and enhance water quality, emphasizing the multifunctional role of wetlands in water management. Similarly, Muto & Yokokawa (2022) highlighted the critical role of wetland paddy fields in floodwater retention and their potential as green infrastructure, which contributes significantly to flood mitigation by implementing effective land-use strategies.

The loss of surface water retention, owing to vegetation succession, is particularly significant in unmanaged farmlands connected to drainage channels. When farmland is left unmanaged, secondary vegetation succession occurs, leading to the re-establishment of vegetation (Haripal *et al*., 2016; Morimoto *et al*., 2022; Weissgerber *et al*., 2023). This process involves gradually replacing cultivated crops with plants and shrubs, which can enhance the soil organic content, nutrient density, and porosity (Nie *et al*., 2024). However, this can also reduce the effectiveness of land in its water storage function. Unused land resulting from the abandonment of cultivation can lead to dense vegetation growth that may not be as effective in storing runoff as managed agricultural land. Emerging vegetation typically develops shallower root systems that fail to penetrate deep into the soil, diminishing its ability to store water (Bueso *et al*., 2023; Hrachowitz *et al*., 2021). Changes in vegetation can alter the hydrological dynamics of an area and affect water infiltration and storage. In this context, the ability of unmanaged farmlands to retain surface water becomes a critical concern when considering the role of paddy fields as natural retention basins. Imai *et al*.

(2022) investigated the effects of abandoning rice cultivation on the floodwater retention function of paddy fields. This study emphasized that hydraulic changes following the abandonment of rice cultivation increase the risk of flooding. Continuous management is essential to prevent vegetation succession and maintain the floodwater retention function, one of the regulating services of artificial wetlands such as paddy fields. Therefore, active management practices are essential to control vegetation succession and maintain land storage capacity.

Monitoring the distribution of vegetation succession in alluvial plains is essential for identifying unmanaged areas undergoing vegetation growth and repurposing them as floodwater storage sites. Extensive studies have been conducted to monitor the succession of vegetation in alluvial floodplains using various monitoring techniques. For example, Van Iersel *et al*. (2016) and Van Iersel *et al*. (2018) investigated the use of unmanned aerial vehicles (UAVs) to monitor seasonal variations of vegetation changes in the height and greenness of floodplain grassland and herbaceous areas. Additionally, Schantz *et al.* (2017) developed methods for establishing long-term vegetation monitoring sites to understand successional transitions in floodplain ecosystems. Although UAVs and on-site monitoring are excellent for localized monitoring of vegetation succession, satellite imagery is crucial for large-scale monitoring. Combining optical and synthetic aperture radar (SAR) satellite images can significantly enhance the accuracy and reliability of vegetation monitoring. For example, Dusseux *et al*. (2014) assessed the ability of optical and SAR images to discriminate between grasslands and crops in agricultural areas, which resulted in improved classification accuracy. Similarly, Polat *et al*. (2022) achieved a higher classification accuracy of combined SAR and optical images for vegetation cover mapping compared to using single data types. While these studies have demonstrated the effectiveness of combining optical and SAR satellite images for vegetation monitoring, there is a gap in utilizing these combined data sources to identify and extract vegetation succession sites. Moreover, although extensive studies (Schantz *et al*., 2017; Van Iersel *et al*., 2016; Van Iersel *et al*., 2018) have been conducted to monitor vegetation succession in alluvial floodplains, there is a notable gap in the studies focusing on identifying and repurposing unmanaged spaces within these plains that have undergone vegetation succession for storage. This gap underscores the need for targeted studies integrating vegetation succession monitoring with flood risk management strategies.

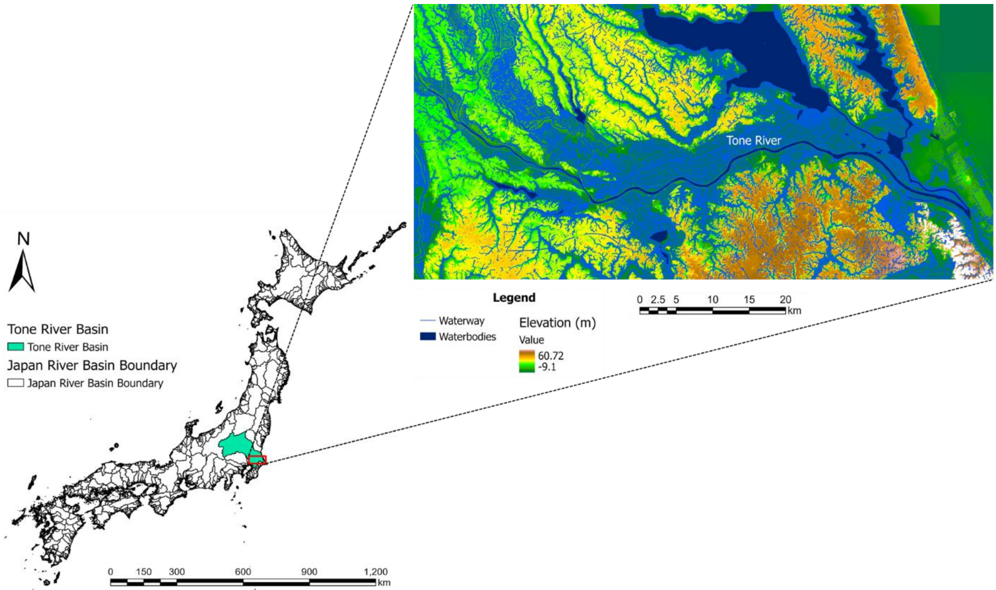
The objective of this study was to discover unmanaged areas within the alluvial plain of the Lower Tone River Basin in Japan that have undergone vegetation succession. By monitoring the distribution of vegetation succession, this study aimed to develop a technical method by integrating optical and SAR satellite images to extract vegetation succession targets over a large landscape and repurposing them as potential floodwater storage spaces through the targeted interventions, including the removal of successional vegetation and the construction of retention ponds, that can be utilized to mitigate inland water flooding. It involves a detailed analysis of changes in vegetation density and structure over the period 2017–2024 to identify vegetation succession sites comprehensively. The period from 2017 to 2024 was specified because of the availability of Sentinel satellite data, which is crucial for monitoring succession. The Sentinel-2 and Sentinel-1 satellites provide high-resolution imagery that is essential for analyzing vegetation density and structure (Polat *et al*., 2022). Monitoring over 7 years enables observing substantial ecological changes, including vegetation succession. Over 7 years, different stages of succession can be observed in the targeted vegetation succession sites, from the initial colonization by grasses and forbs to the establishment of shrubs (Poorter *et al*., 2024).

MATERIALS AND METHODS

Study Area

The Tone River Basin, covering approximately 16,840 km^2, is the largest river basin in Japan. As one of the nation's principal rivers, the Tone River extends roughly 322 km from Gunma Prefecture to the Pacific Ocean in Chiba Prefecture, according to the Ministry of Land, Infrastructure, Transport and Tourism Kanto Regional Development Bureau (https://www.ktr.mlit.go.jp/tonejo/tonejo00182.html). This study focused on the Lower Tone River Basin, a crucial segment of the Tone River system, as illustrated in Fig. 1. This portion of the river traverses the Kanto Plain, which is distinguished by its flat, low-lying terrain. Flooding in the Lower Tone River Basin is a major concern, primarily because of its geomorphological and hydrological characteristics. Oya (1969) demonstrated that the geomorphology of the Tone River Basin, especially in its lower reaches, significantly contributes to flood risk. Additionally, climate change has exacerbated flood risk in the Lower Tone River Basin (Kim *et al*., 2011). According to the Tone River Downstream Office (https://www.ktr.mlit.go.jp/tonege/tonege00563.html), they developed the River Basin Flood Control Project 2.0 in the lower reaches of the Tone River to accelerate and deepen river basin flood control to address the increasing risk of water-related disasters anticipated from future climate change and implement early-stage disaster prevention and mitigation strategies in response to increased rainfall. Consequently, it is necessary to strategically disperse storage spaces in the alluvial plain of the Lower Tone River Basin to store floodwater from drainage channels.

Fig. 1: Study area



Data Collection and Pre-processing

This study entailed the acquisition and pre-processing of diverse geospatial datasets, as shown in Table 1. The Digital Elevation Model (DEM) used was DEM5A, procured via aerial laser surveying. This dataset, with a spatial resolution of 5 m, was sourced from the Geospatial Information Authority of Japan (GSI) on January 17, 2020. Pre-processing of the

DEM involved georeferencing and rectifying elevation voids using ArcGIS Pro 3.1. The Digital Topographic Map 25000, a land condition map in vector format, offers topographic classifications instrumental in selecting specific land conditions. Acquired from the GSI in 2013, this dataset is vital for understanding various landforms within the alluvial plains. Georeferencing was executed using ArcGIS Pro 3.1 to synchronize the map with other geospatial datasets. Optical satellite imagery from Sentinel-2 Level-2A was used to monitor vegetation density succession.

Table 1: Summary of data collection and pre-processing

Data type	Specification	Spatial resolution (m)	Acquisition date	Data source	Pre-processing steps	Pre-processing software
Digital Elevation Model	Elevation - aerial laser surveying	5	January 17, 2020	GSI	Georeferencing Elevation void fill	ArcGIS Pro 3.1
Digital Topographic Map 25000	Vector format of topographic classifications	-	2013	GSI	Georeferencing	ArcGIS Pro 3.1
Optical Satellite Images	Sentinel-2 Level-2A B4 (Red) and B8 (VNIR)	10	August 8, 2017 August 11, 2024	CDSE	Georeferencing Resampling	SNAP
SAR Satellite Images	Sentinel-1 C-SAR Level-1A GRD IW Swath VV + VH Polarization	10	August 13, 2017 August 12, 2024	CDSE	Georeferencing Apply orbit file Radiometric calibration Speckle filtering Terrain correction Resampling	SNAP
Land Use Land Cover Map	HRLULC Map	10	April 1, 2022	JAXA EORC	Georeferencing	ArcGIS Pro 3.1
Waterline Map	Polyline map of drainage channels	-	July 31, 2014	GSI	Georeferencing	ArcGIS Pro 3.1

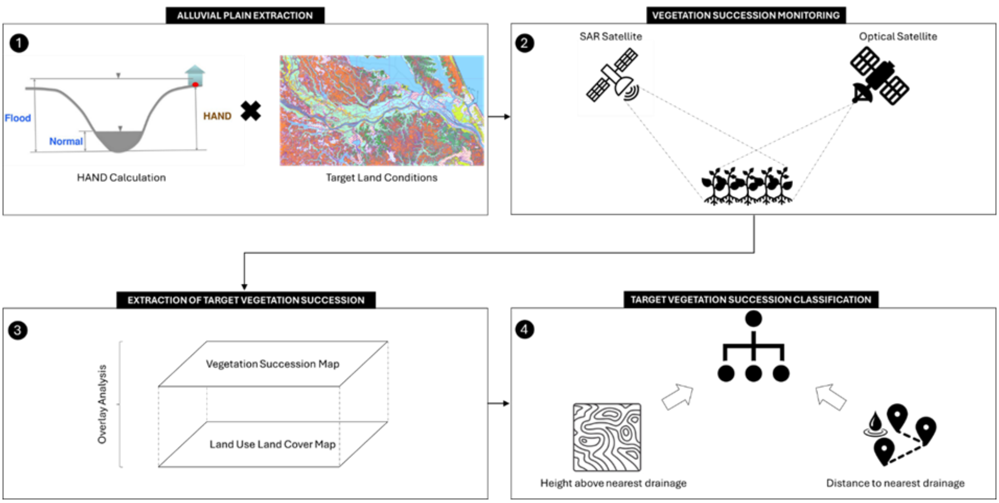
These images, captured on August 8, 2017, and August 11, 2024, from the Copernicus Data Space Ecosystem (CDSE) during the peak vegetation growing season, provide high-resolution data with a spatial resolution of 10 m. The bands used included B4 (red) and

B8 (visible and near-infrared (VNIR)). The pre-processing steps encompassed georeferencing and resampling using the Sentinel Application Platform (SNAP). SAR satellite images from the Sentinel-1 C-SAR Level-1A ground range detection (GRD) were utilized to observe vegetation structure succession. These images, acquired on August 13, 2017, and August 12, 2024, from the CDSE, also during the peak growing season, possessed a spatial resolution of 10 m and used an interferometric wide (IW) swath and VV + VH polarization. The SAR images underwent extensive pre-processing, including georeferencing, application of orbit files, radiometric calibration, speckle filtering, terrain correction, and resampling, all of which were performed using SNAP. The high-resolution land use and land cover (HRLULC) map obtained from the Japan Aerospace Exploration Agency (JAXA) Earth Observation Research Centre (EORC) on April 1, 2022, provided detailed insights into land-use patterns within the alluvial plain. With a spatial resolution of 10 m, this map was overlaid with a vegetation succession map to facilitate the analysis of vegetation succession across different land-use categories. Georeferencing was performed using ArcGIS Pro 3.1 to ensure accurate alignment of the map with other datasets. The waterline map acquired from the GSI on July 31, 2014, offers shapefile data with a polyline representation of the drainage channels. This map was used to compute the distance from the vegetation succession patches to the nearest drainage channel, a crucial parameter for understanding the spatial relationship between land and water channels for flood control. Georeferencing was conducted using ArcGIS Pro 3.1 to align the waterline map with other geospatial datasets.

Analytical Flow

The analytical framework of this study followed a systematic approach, as illustrated in Fig. 2. The initial step involved extracting alluvial plain areas using a DEM and a land condition map. This phase is crucial for accurately defining the study area and comprehending the topographical features that are prone to flooding. Subsequently, the succession in vegetation density and structure was monitored using optical and SAR satellite images from 2017 to 2024.

Fig. 2: Analytical framework



This involved scrutinizing satellite data to observe how vegetation evolves in response to unused land management and the extraction of vegetation succession sites. The next phase of the study was to analyze the relationship between land-use types and vegetation succession patterns within the alluvial plain. This phase aimed to reveal the land-use type distribution in the alluvial plain and emphasize the vegetation succession ratio in each land-use type, leading to the extraction of target vegetation succession sites within the wetlands around agricultural areas. Finally, these target vegetation succession patches were classified based on parameters such as the height above the nearest drainage, distance to the nearest drainage channel, and other parameters. This classification aimed to establish functional groupings of succession sites, which are critical for designing targeted flood control strategies.

Alluvial Plain Extraction

The initial phase involved calculating the height above nearest drainage (HAND) using the DEM. HAND (Nobre *et al*., 2011) is a topographic metric that measures the vertical distance of each point in the landscape above the nearest drainage channel, thereby identifying areas at risk of flooding (Johnson *et al*., 2019; Thalakkottukara *et al*., 2024). The DEM was processed to determine the elevation of each pixel relative to the nearest drainage channel to compute HAND. This involves generating a flow direction grid to trace the paths that water would follow across the landscape and then calculating the vertical distance from each pixel to the nearest drainage path. The HAND values were computed across the study area using ArcGIS Pro 3.1. Following the calculation of HAND, the subsequent step involved selecting specific land conditions from the Digital Topographic Map 25000. The target land conditions included coastal plains, deltas, reclaimed lands, old river channels, natural levees, valley plains, and floodplains. These landforms were chosen because of their significant functions in alluvial plain dynamics and inherent susceptibility to flooding. The final phase of the alluvial plain extraction process involved delineating the alluvial plain area based on HAND values and selected land conditions, as detailed in Table 2. Alluvial plain areas were identified where HAND values were less than or equal to 3 m, indicating a low elevation relative to the drainage channels.

Table 2: Dual-criteria for alluvial plain extraction

HAND	≤ 3 m
Land Conditions	Coastal plains Deltas Reclaimed lands Old river channels Natural levees Valley plains Floodplains

The 3 m threshold was selected considering levee overtopping heights and empirical flood records for the Lower Tone River. Retarding basins such as Tanaka, Sugo, and Inadoi typically activate at this elevation during peak flood events, suggesting hydraulic connectivity between channels and adjoining plains (Matsumoto *et al*., 2013). Furthermore, hydrological modelling protocols commonly apply HAND thresholds within the 2 to 5 m range to define inundation-prone floodplain extents (Thalakkottukara *et al*., 2024). Consequently, areas with HAND ≤ 3 m are both physically susceptible and historically documented as flood-prone. Additionally, these areas must correspond to the selected land conditions. This dual-criterion approach ensured that the delineated alluvial plain areas were accurately identified based on both elevation and landform characteristics.

Vegetation Succession Monitoring

The normalized difference vegetation index (NDVI) (Amiri & Pourghasemi, 2022; Huang *et al*., 2021) is a widely recognized metric for assessing vegetation density. It was derived from Sentinel-2 satellite images. The NDVI was calculated by comparing the difference between near-infrared light (which vegetation strongly reflects) and red light (which vegetation absorbs) using Equation (1):

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

where NIR represents the near-infrared band (B8), and Red denotes the red band (B4). The resulting NDVI values range from −1 to 1, with higher values indicating denser and healthier vegetation. By computing the changes in the NDVI between 2017 and 2024, we assessed temporal variations in vegetation density.

The radar vegetation index (RVI) (Hu et al., 2024; Nasirzadehdizaji *et al*., 2019; Szigarski *et al*., 2018) was used to monitor the vegetation structure and was derived from SAR Sentinel-1 images. SAR data are particularly advantageous for vegetation monitoring because they can penetrate cloud cover and provide information on vegetation structure irrespective of weather conditions. The RVI was calculated using dual-polarization (VV and VH) data from SAR images using formula (2):

$$RVI = \frac{4 * \sigma_{VH}^0}{\sigma_{VV}^0 + \sigma_{VH}^0} \quad (2)$$

where σ_{VV}^0 and σ_{VH}^0 represent the co-polarized and cross-polarized backscatter coefficients, respectively. The RVI values offer insights into the structural complexity of vegetation. This step aimed to understand the structural succession in vegetation over time by analyzing changes in the RVI from 2017 to 2024.

In this study, vegetation succession areas were identified based on significant changes in the NDVI and RVI values. We used a specific threshold of NDVI change values ≥0.2 and RVI change values >0 to pinpoint these areas, as illustrated in Table 3. NDVI change values ≥0.2 typically indicate sparse to dense vegetation, whereas RVI change values >0 highlight areas with vegetation growth. Thresholds of NDVI ≥ 0.20 and RVI > 0.0 were selected for their ecological significance and proven reliability in remote-sensing applications. NDVI values between 0.20 to 0.50 typically correspond to moderate vegetation cover, such as grassland and early succession shrubs, as documented by the U.S. Geological Survey (USGS) remote-sensing phenology guidelines (https://www.usgs.gov/special-topics/remote-sensing-phenology/science/ndvi-foundation-re mote-sensing-phenology). Furthermore, ecological studies indicated that NDVI shifts of approximately 0.20 consistently mark meaningful phenological transitions, whereas smaller variations often reflect sensor noise or atmospheric artifacts (Huang *et al*., 2021). Similarly, positive changes in RVI have been shown to directly correlate with biomass accumulation and structural development, as demonstrated in radar-based vegetation monitoring research (Szigarski *et al*., 2018). These thresholds ensured that only regions with notable increases in vegetation density and structure were considered as vegetation succession sites. The adoption of threshold methods for identifying areas of vegetation succession was a crucial aspect of this study. Thresholding simplifies the data analysis process by categorizing continuous data into target classes. This simplification is essential for ecological studies involving large datasets (López *et al*., 2011). Moreover, the threshold method enhanced the efficiency of data processing. Handling continuous data is complex and computationally intensive. By applying thresholds, this study reduced this complexity, allowing for quicker and more efficient data processing. This efficiency is important in remote sensing studies, where the timely analysis of large datasets is often required (Descals *et al*., 2021; Xing *et al*., 2022). Therefore, the identified areas were mapped to provide a comprehensive overview of the vegetation succession sites within the alluvial plain.

Table 3: Thresholds for vegetation succession extraction

NDVI change value	≥0.2
RVI change value	>0.0

Extraction of Target Vegetation Succession

Analyzing vegetation succession within different land-use types is essential for understanding the variability and distribution of vegetation succession sites across the alluvial plain of the Lower Tone River Basin. This process overlaps vegetation succession data with the land use land cover (LULC) map to discern vegetation succession patterns within various land-use categories. The initial step involved conducting an overlay analysis, specifically a union analysis, using ArcGIS Pro 3.1. This analysis combined the vegetation succession map, highlighting areas of significant vegetation growth, with the LULC map, which categorizes the landscape into various land-use types. Union analysis integrated these two datasets, offering a comprehensive view of how vegetation succession occurs across different land-use types in the alluvial plain landscape. Following the overlay analysis, the next step involved extracting target vegetation succession sites located within wetlands adjacent to agricultural areas. Wetlands were prioritized due to their critical role in floodwater storage and adaptive capacity. This process focused on selecting only those succession sites that satisfied all NDVI and RVI threshold criteria established in the previous step, while restricting the analysis to the defined wetland zones and excluding other land-use types. Identifying these areas is essential because vegetation succession within wetlands can compromise their natural storage function. Consequently, repurposing these sites through interventions such as vegetation clearance and pond construction is strongly recommended to restore and enhance their capacity for floodwater retention.

Target Vegetation Succession Classification

The classification process was initiated by preparing input parameters, including HAND, distance to the nearest drainage channel, NDVI change value, RVI change value, patch length, and patch area. Zonal statistics in ArcGIS Pro 3.1 were utilized to extract HAND values for each vegetation succession patch. The distance from each vegetation succession patch to the nearest drainage channel was determined using the near-analysis tool in ArcGIS Pro 3.1. By focusing on the vegetation succession patches within the wetlands around the agricultural areas of the alluvial plain, waterways can be considered as drainage channels to determine the distance from each vegetation succession patch to the nearest drainage channel. The NDVI and RVI change values, along with patch length and area, were obtained from the vegetation succession monitoring phase. A combination of these input parameters was selected to provide an understanding of vegetation succession characteristics and prioritize regions for floodwater storage. Each parameter provided unique insights into the hydrological, structural, and spatial characteristics of the vegetation succession patches. After preparing the independent parameters, unsupervised vegetation succession classification was conducted using the TwoStep cluster analysis in IBM SPSS Statistics 27. This method is particularly effective for managing large datasets and identifying natural groupings within them. The quality and stability of the clusters were assessed by evaluating the silhouette coefficient, which measures the similarity of an object to its own cluster compared to other clusters, to validate the clustering results. A summary of the model settings for vegetation succession classification is presented in Table 4.

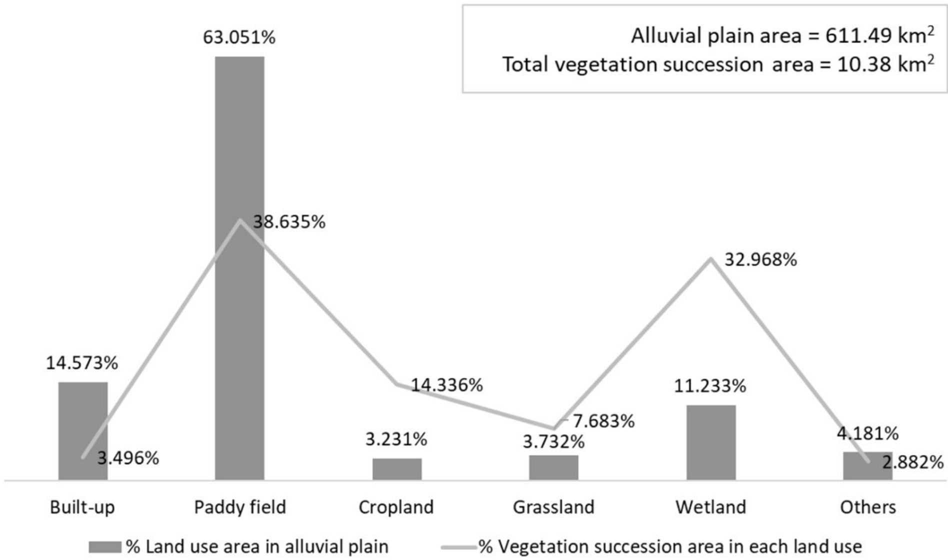
Table 4: Summary of classification model settings

Input parameters	Height above nearest drainage (m)
	Distance to nearest drainage channel (m)
	NDVI change value
	RVI change value
	Patch length (m)
	Patch area (m^2)
Classification method	TwoStep cluster analysis
Clustering criterion	Schwarz's Bayesian criterion (BIC)
Distance measure	Log-likelihood
Number of clusters	Determine automatically
Validation measure	Silhouette coefficient

RESULTS

The findings of this study offer a detailed understanding of land-use distribution and vegetation succession distribution across various land-use types within the alluvial plain of the Lower Tone River Basin. Figure 3 presents these results, showing the spatial ratio of land-use types and vegetation succession areas for each land-use type throughout the study area. In the alluvial plain of the Lower Tone River Basin, which covered 611.49 km^2, the land-use distribution predominantly comprised paddy fields, which occupy 63.051 % of the area. Built-up areas constituted 14.573 %, while wetlands made up 11.233 %. This distribution highlights that agricultural land, particularly paddy fields, is the primary land-use type in the region, followed by urban development and wetland areas. The study also uncovered significant vegetation succession areas within these land-use types. Of the total vegetation succession area of 10.38 km^2, the majority occurred in paddy fields, representing 38.635 % of the vegetation succession area. The wetlands closely followed, accounting for 32.968 % of the vegetation succession. This indicated that paddy fields and wetlands are the primary zones of vegetation succession influencing their storage functions. Furthermore, the study identified 1582 target vegetation succession patches within wetlands adjacent to agricultural areas, highlighting priority sites for potential intervention.

Fig. 3: Land-use ratio and vegetation succession ratio in each land-use type within the alluvial plain



The classification of target vegetation succession patches within wetlands around agricultural areas of the alluvial plain provides valuable insights into the spatial ratio and attributes of vegetation succession patches for each class. Fig. 4 illustrates these results by categorizing the patches of vegetation succession into three classes. Clustering analysis, validated by a silhouette coefficient of 0.75, indicated a high quality of cluster separation and cohesion. Class 1 included the majority of vegetation succession patches, with 614 patches accounting for 38.81 % of the total patches. These patches were characterized by the lowest average height above the nearest drainage of 0.2 m and the closest average distance to the nearest drainage channels of 10.692 m. The average patch length was 271.43 m, and the average patch area was 2852.44 m^2. Class 1 patches exhibited the greatest changes in both the mean NDVI of 0.27720 and the mean RVI of 0.04674 change values, indicating significant vegetation density and structural succession. Class 2 comprised 600 vegetation succession patches, representing 37.93 % of the total. These patches had an average height above the nearest drainage of 0.978 m, and were located at an average distance of 15.304 m from the nearest drainage channel. The average patch length was 277.50 m, and the average patch area was 3124.67 m^2, making them the largest patches in terms of area. The mean NDVI change for Class 2 was 0.27529, and the mean RVI change was 0.04487, which was slightly lower than that of Class 1. Class 3 comprised 368 vegetation succession patches, accounting for 23.26% of the total patches. These patches were situated at the highest average elevation above the nearest drainage of 2.007 m and the furthest average distance from the nearest drainage channels of 16.517 m. The average patch length was 216.90 m, and the average patch area was 1761.68 m^2, making them the smallest patches. The mean NDVI change for Class 3 was 0.26774, and the mean RVI change was 0.04331, which was the lowest among the three classes.

Fig. 4: Attributes of vegetation succession classification: (a) ratio of vegetation succession classes, (b) patch size of vegetation succession classes, (c) succession rate of vegetation succession classes, and (d) position of vegetation succession classes

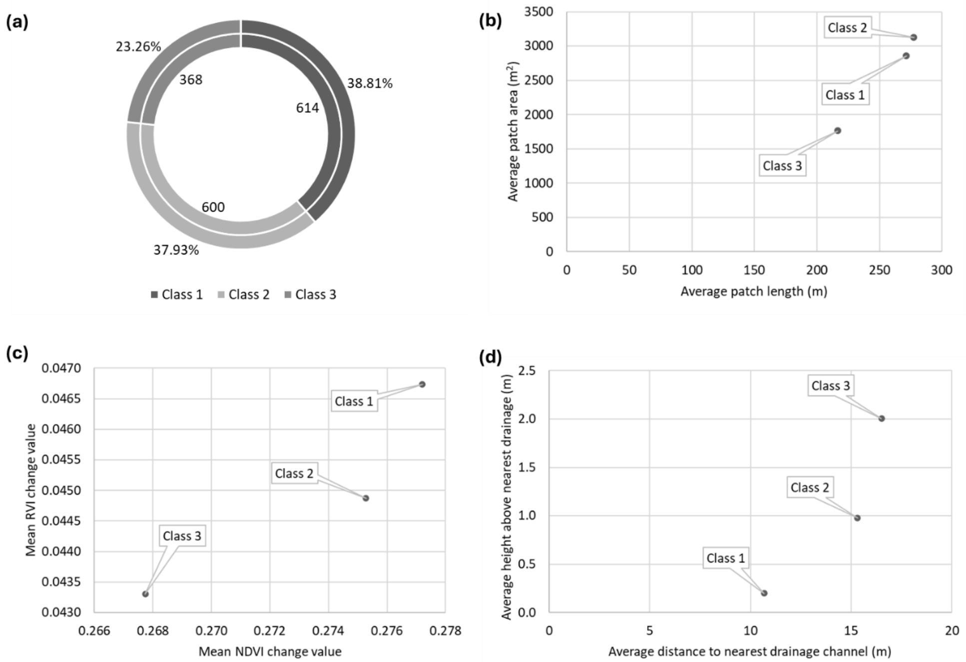


Fig. 5 shows the distribution of vegetation succession classes within the alluvial plain of the Lower Tone River Basin. This figure highlights the spatial extent of different classes. Class 1, illustrated by red patches, comprised 614 vegetation succession patches dispersed across the landscape. These patches were characterized by the lowest elevation, closest proximity to drainage channels, and significant changes in vegetation density and structure. Class 2, depicted as green-colored patches, included 600 vegetation succession patches spread throughout the alluvial plain. These patches were moderately elevated, with intermediate distances to the drainage channels and substantial changes in vegetation density and structure. Class 3, shown as blue patches, consisted of 368 vegetation succession patterns across the landscape. These patches were situated at the highest elevations and furthest distances from the drainage channels, exhibiting the least dynamic changes in vegetation density and structure.

Fig. 5: Spatial distribution map of vegetation succession classes

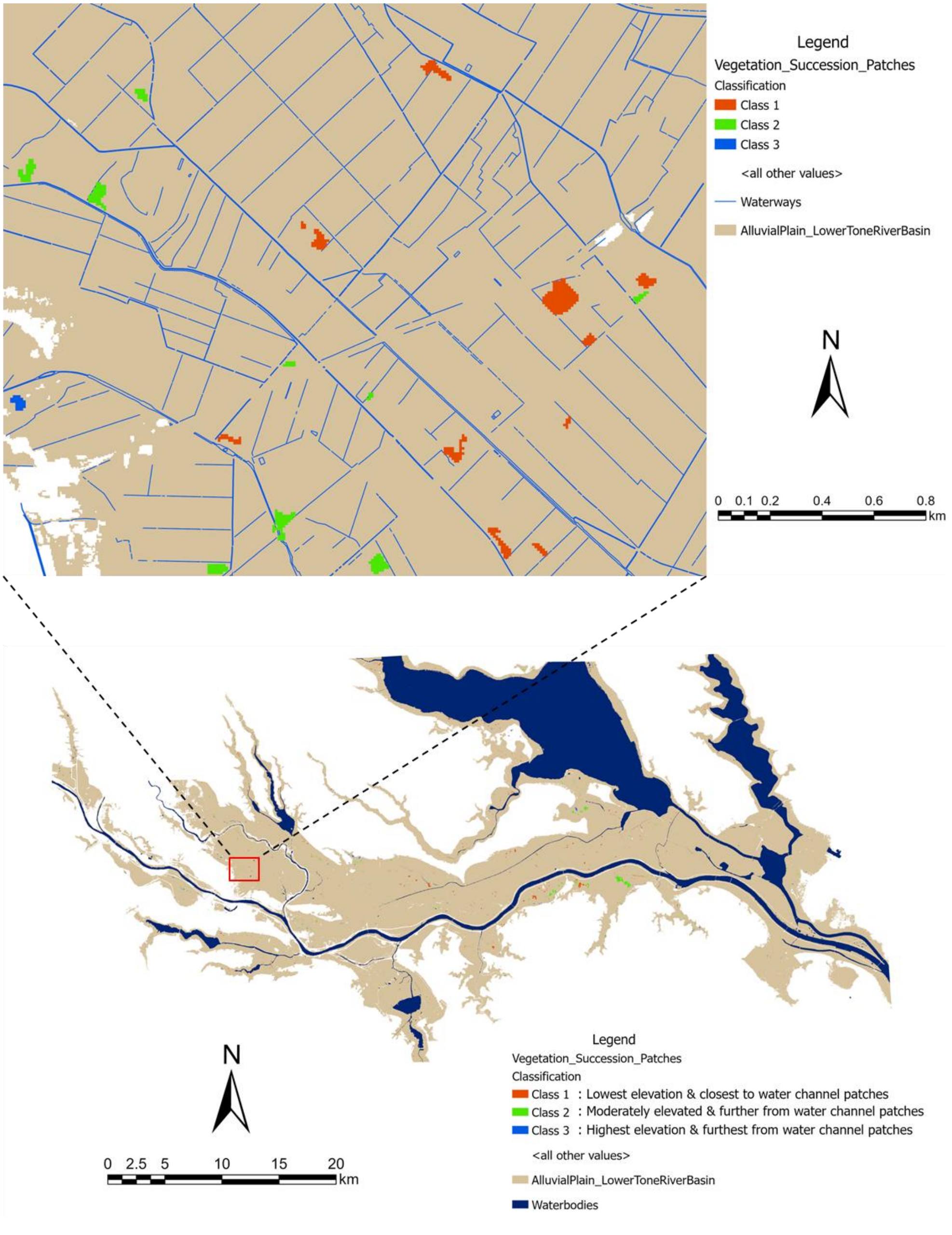
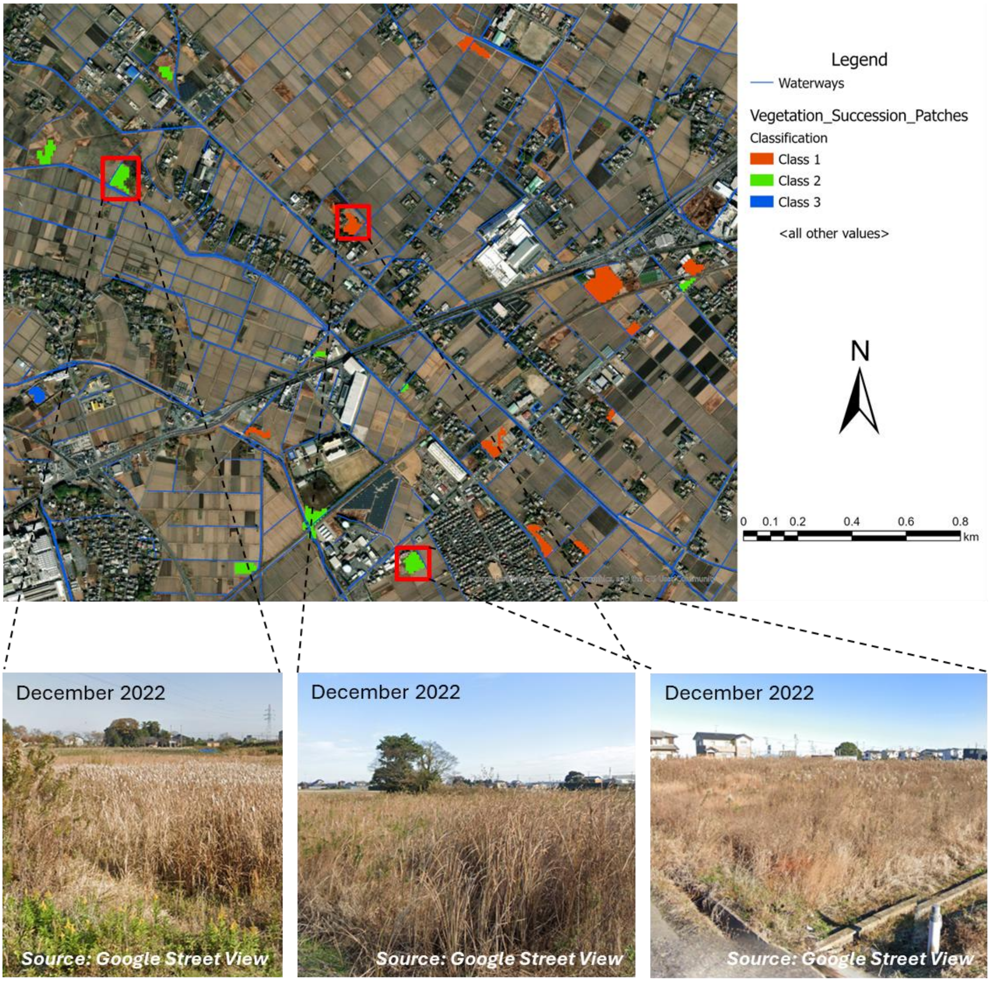


Fig. 6 illustrates representative examples of vegetation succession sites identified using the methodological framework developed in this study. These sites were captured using Google Street View imagery, with three specific locations highlighted as undergoing vegetation succession. Although the images were captured in December 2022, during the winter season when vegetation is typically not green, the visual evidence indicated that these areas are in unmanaged conditions, revealing the absence of cultivation and a state of vegetation succession. Google Street View served as a supplementary ground-level validation tool, offering direct visual confirmation of succession sites. This approach provides a practical and cost-effective alternative for verifying vegetation succession when field surveys or high-resolution satellite imagery are not feasible. This observation supported the validity of the developed methodology, which integrates optical and SAR satellite imagery to identify vegetation succession sites effectively.

Fig. 6: Example of identified vegetation succession sites (images captured from Google Street View)



DISCUSSION

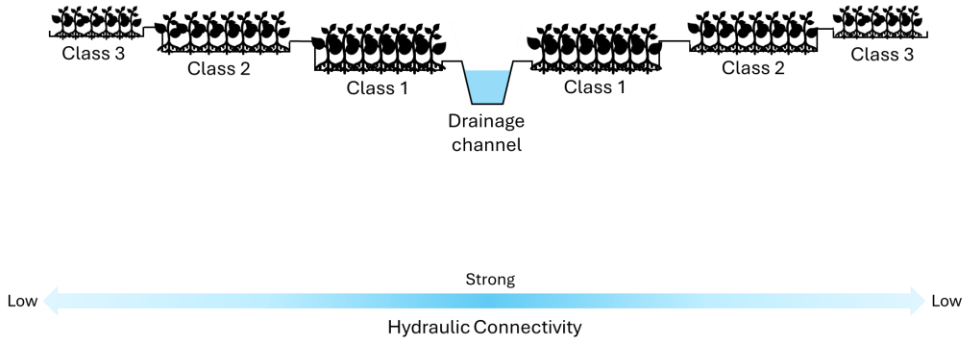
Vegetation Succession Classes

The classification of vegetation succession patches within wetlands around the agricultural areas of the alluvial plain offers crucial insights into their spatial configuration, especially in the context of land-water interactions. Zweig &Kitchens (2009) investigated the intricate nature of wetland ecosystems and the succession mechanisms, underscoring the pivotal role of hydrology in driving multi-state transitions within wetland communities.

As illustrated in Fig. 7, the three vegetation succession classes, class 1, class 2, and class 3, demonstrate unique characteristics that significantly influenced their functional role in flood control through variations in hydraulic connectivity. Class 1 patches were distinguished by their proximity to drainage channels and low elevations relative to the nearest drainage points. These patches exhibited the most significant changes in NDVI and RVI, reflecting substantial vegetation density and structural succession. Their proximity to water sources, showing a strong hydraulic connectivity, enhances their capacity to store floodwater, making these highly dynamic areas crucial for immediate floodwater storage. Mitsch *et al*. (2012) emphasized the importance of hydrology in wetland development, noting that Class 1 patches, which are close to drainage channels, benefit from a consistent water supply, which is crucial for robust vegetation growth and succession. Additionally, Class 1 patches, with their proximity to water sources, can effectively store floodwater. Class 2 patches, while moderately dynamic, were situated at higher elevations and farther from drainage channels than Class 1 patches. These patches encompass a large area and facilitate substantial floodwater storage. The moderate changes in NDVI and RVI suggested that these patches are less dynamic than Class 1 patches. A larger patch area contributes to the overall flood mitigation efforts by repurposing as an intermediate storage area, balancing immediate and long-term floodwater management. Odland (2024) highlighted the influence of elevational gradients on plant distribution and dynamics in floodplain wetlands. Class 2 patches, situated at higher elevations and further away from drainage channels, align with the finding that elevation affects vegetation succession and hydrological responses. Additionally, Class 2 patches, with their larger areas, contribute substantially to floodwater storage. Class 3 patches were located at the highest elevations above the nearest drainage points and furthest from the drainage channels, indicating low hydraulic connectivity. These patches showed the smallest changes in NDVI and RVI, indicating less dynamic vegetation succession. Despite their higher and farther locations from water sources, Class 3 patches are essential to the overall flood control strategy because they can be repurposed as final storage spaces for dispersed floodwater. Tang *et al*. (2020a) emphasized optimizing the wetland storage capacity to mitigate downstream flooding. Class 3 patches, situated at higher elevations, align with utilizing elevated areas as final storage spaces to manage dispersed floodwater effectively. Thus, Class 3 patches contribute to flood mitigation by serving as the final storage areas for floodwater.

Because Classes 1, 2, and 3 represent unmanaged spaces undergoing vegetation succession, their capacity for surface water retention has been diminished. Woody succession, in particular, induces significant losses in retention through various interacting hydrological processes. As succession progresses, the development of litter layers and deeper root systems creates heterogeneous surface roughness, leading to uneven ponding and accelerating drainage via preferential flow paths (Kovář *et al*., 2013; Štefánek *et al*., 2018; Trautmann *et al.,* 2022). Additionally, increased woody cover markedly elevates evapotranspiration (ET), reducing surface water storage and redirecting retained water into biomass or soil moisture (Schreiner-McGraw *et al*., 2020). In semi-arid to sub-humid environments, this shift typically transforms storage dynamics away from surface retention (Wilcox *et al*., 2022). To restore the floodwater storage function of these unmanaged spaces, this study proposes targeted interventions such as clearing successional vegetation and converting these areas into constructed ponds. Such measures would re-establish surface retention capacity and strengthen their role in flood risk mitigation strategies.

Fig. 7: Characteristics of vegetation succession classes considering hydraulic connectivity

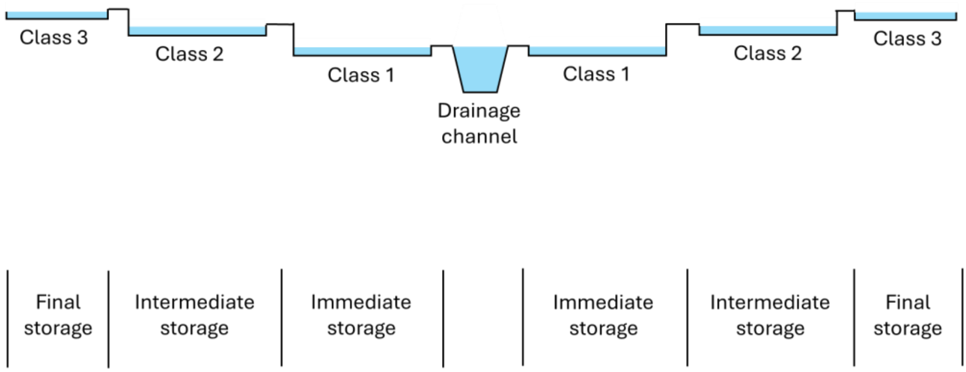


Proposed Storage Functionality

Understanding the functional relationship among the three classes following the proposed interventions is vital for effective flood control and management, particularly in the context of inland water flooding. Depending on on-site conditions, flooding that primarily originates from drainage channels affects differently across Classes 1, 2, and 3. Class 1 spaces are paramount for immediate floodwater storage. Maximizing the storage capacity of these spaces is crucial because they can quickly respond to mitigate floodwater. Moridi & Yazdi (2017) supported optimizing the storage capacity in Class 1 spaces. The principles of dynamic water level management and strategic storage allocation can be applied to Class 1 spaces to enhance their floodwater storage capacity. Class 2 spaces are crucial buffers for managing floodwater dispersed from Class 1 spaces and provide additional storage capacity. By acting as intermediate storage, Class 2 spaces help manage floodwater before it reaches Class 3 spaces. Ferreira *et al*. (2021) highlighted the importance of a network of connected NbS elements in improving flood mitigation and enhancing resilience. This aligns with the role of Class 2 spaces in providing additional storage capacity and balancing floodwater management across the landscape, ensuring that they function efficiently as buffers between Classes 1 and 3. Class 3 spaces are integral to serving as final storage spaces for dispersed floodwaters. Ensuring that Class 3 spaces function effectively as final storage spaces is vital for comprehensive flood control, as they help manage floodwater that spreads widely across the landscape. Brody & Highfield (2013) highlighted that expansive and continuous patches of naturally occurring open spaces can significantly reduce flood losses. These findings support the role of Class 3 spaces in providing essential storage capacity for floodwater that has traveled through Classes 1 and 2. Additionally, the study by Tang *et al.* (2020b) investigated how the location and size of wetlands influence downstream flooding within a watershed. These findings can be applied to understand how Class 3 spaces, with their higher elevation and distance from water sources, can serve as final storage spaces for dispersed floodwater.

The functional relationship among Classes 1, 2, and 3 is characterized by the sequential impact of inland water flooding based on on-site conditions, as depicted in Fig. 8. Initially, floodwater from drainage channels impacts the Class 1 spaces, which store the initial influx of water. As the floodwater disperses, it reaches Class 2 spaces, which provide intermediate storage and further manage the floodwater. Finally, Class 3 spaces serve as the last line of mitigation, storing floodwater spread widely across the landscape. Accordingly, the identified unmanaged spaces should be prioritized for conversion into functional storage areas by restoring their surface water retention capacity through targeted interventions, including the removal of successional vegetation and the construction of retention ponds.

Fig. 8: Proposed storage functionality among classes considering on-site conditions



Vegetation Monitoring Method and Limitations

The methodological approach used in this study to extract vegetation succession sites was both innovative and comprehensive, leveraging the strengths of combined optical and SAR satellite imagery. This integration enables monitoring vegetation growth over time, providing a robust framework for identifying areas undergoing vegetation succession. This study used NDVI and RVI as key vegetation indices to monitor changes in vegetation density and structure. Similarly, a previous study by Kirbizhekova *et al*. (2024) presented a method for assessing forest regrowth dynamics using both the NDVI and RVI, introducing a novel approach by plotting vegetation changes on the NDVI and RVI planes. Another study by Narin *et al*. (2022) demonstrated the effectiveness of combining the NDVI and RVI time series from Sentinel-2 and Sentinel-1 satellites to distinguish crop types and monitor changes, which could be adapted for vegetation succession analysis. In our study, both the NDVI and RVI values were calculated for 2017 and 2024, allowing for the assessment of vegetation density and structural changes over these 7 years. Specific thresholds were applied to the changes in NDVI and RVI values to identify and extract areas undergoing vegetation succession. Similarly, Islam *et al*. (2023) used NDVI differencing and applied specific NDVI threshold values (e.g., 0, 0.1, 0.15, and 0.2) to classify and detect vegetation changes over time, validating the use of NDVI with threshold-based methods for multi-year vegetation change detection.

However, the methodological approach for extracting vegetation succession sites in this study presents several technical limitations that require further investigation. Threshold and temporal issues are two primary areas of concern, both of which are critical for identifying vegetation succession targets. One of the key technical challenges is determining appropriate thresholds for extracting significant changes in the vegetation indices. Future studies should optimize these thresholds to enhance the sensitivity and specificity of vegetation succession detection. The temporal aspect is another critical area for future investigation. Vegetation succession is a continuous process that can vary significantly over short and long timescales. A key limitation of this study lies in its restricted temporal scope (2017-2024), which may not fully capture long-term successional dynamics. Since succession often unfolds over decades, short observation windows risk overlooking gradual structural changes and seasonal variability. Future studies should explore the impacts of different temporal resolutions on the accuracy of vegetation succession monitoring and extraction.

CONCLUSIONS

This study focused on identifying vegetation succession sites to discover unmanaged areas that could be repurposed as storage zones for inland water flooding within the alluvial plain of the Lower Tone River Basin in Japan. This study addresses the reduction in surface water retention caused by vegetation succession, particularly in unmanaged farmlands connected to drainage channels. By identifying and classifying the distribution of vegetation succession sites using a combination of optical and SAR satellite images, this study proposes a possible storage function restoration for these unmanaged spaces through the intervention of vegetation clearance and pond construction. The classification of vegetation succession yielded key insights into the ecological succession of unused spaces and their implications for storage. Through cluster analysis, vegetation succession patches were categorized into three classes based on elevation, proximity to drainage channels, and variations in the NDVI and RVI. Class 1 spaces, characterized by close association with water sources, were identified as critical zones for immediate floodwater storage. Class 2 spaces functioned as intermediate storage areas that balanced immediate- and long-term floodwater management. Class 3 spaces, situated at the highest elevation and furthest from the drainage channels, serve as the final storage spaces for dispersed floodwaters. These spaces play a vital role in long-term flood management by acting as final storage zones for floodwater traversing through Class 1 and Class 2 spaces. This study provides valuable insights into the ecological succession of unmanaged spaces and their implication for flood control in the alluvial plain of the Lower Tone River Basin. By identifying and categorizing unmanaged areas, this study offers a foundation for prioritizing intervention areas and developing targeted flood mitigation strategies. These findings can inform land-use planning and watershed management, aid communities in optimizing the storage function of unmanaged spaces, and enhance flood control measures.

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CONFLICT OF INTEREST

The authors report there are no competing interests to declare.

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