

ENHANCING AGRICULTURAL DRAINAGE RESILIENCE UNDER CLIMATE CHANGE: A CASE STUDY OF INTEGRATED AND SMART DRAINAGE PUMP STATION MANAGEMENT IN BUYEO COUNTY, KOREA

AMÉLIORER LA RÉSISTANCE DU DRAINAGE AGRICOLE FACE AU CHANGEMENT CLIMATIQUE : UNE ÉTUDE DE CAS SUR LA GESTION INTÉGRÉE ET INTELLIGENTE D'UNE STATION DE POMPAGE DANS LE COMTÉ DE BUYEO, CORÉE

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ABSTRACT

Climate change has increased the frequency and intensity of extreme rainfall events, resulting in greater flood risks in low-lying agricultural regions. In Korea, many agricultural drainage systems were designed under outdated hydrological conditions and are no longer capable of effectively managing current rainfall patterns. Buyeo County, characterized by extensive paddy fields, flat topography, and clay-rich soils with low permeability, has experienced repeated farmland inundation and crop damage over the past decade despite the presence of multiple drainage pump stations. This study investigated the major causes of agricultural flooding in Buyeo County and proposed a smart and integrated drainage management framework to improve resilience under climate change. An integrated assessment was conducted using historical flood records, rainfall data, topographic information, soil drainage characteristics, and operational data from drainage pump stations. The results showed that recent increases in short-duration, high-intensity rainfall frequently exceeded the drainage capacity of existing facilities. In addition, poor natural drainage conditions, insufficient pumping capacity, delayed pump operation, and lack of coordination among neighboring facilities significantly increased flood vulnerability.

Keywords: Climate change; Agricultural flooding; Agricultural drainage; Drainage pump stations; Extreme rainfall; Flood resilience; Smart drainage management.

RESUME

Le changement climatique a augmenté la fréquence et l'intensité des événements de précipitations extrêmes, donnant lieu au risque accru d'inondation dans les basses terres agricoles. En Corée, de nombreux systèmes de drainage agricole ont été conçus selon les conditions hydrologiques obsolètes et ne sont plus capables de gérer efficacement les régimes pluviométriques actuels. Le comté de Buyeo, caractérisé par de vastes rizières, une topographie plate et des sols riches en argile à faible perméabilité, a connu des inondations répétées de terres agricoles et des dommages aux cultures au

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cours de la dernière décennie malgré la présence de plusieurs stations de pompage de drainage. Cette étude a étudié les principales causes des inondations agricoles dans le comté de Buyeo et a proposé un cadre de gestion intelligente et intégrée du drainage afin d'améliorer la résistance face au changement climatique. Une évaluation intégrée a été faite à l'aide de relevés historiques des inondations, de données sur les précipitations, d'informations topographiques, de caractéristiques du drainage des sols et de données opérationnelles provenant de stations de pompage. Les résultats ont montré que l'augmentation récente des précipitations de courte durée et de forte intensité dépassait fréquemment la capacité de drainage des installations existantes. En outre, les mauvaises conditions de drainage naturel, la capacité de pompage insuffisante, le fonctionnement tardif des pompes et le manque de coordination entre les installations voisines ont considérablement augmenté la vulnérabilité aux inondations.

Mots-clés : Changement climatique; Événements de précipitations extrêmes; Stations de pompage de drainage; Capacité de drainage.

1. INTRODUCTION

Climate change has significantly increased the frequency and intensity of extreme rainfall events worldwide, leading to recurrent flooding in agricultural regions. In Korea, short-duration heavy rainfall events exceeding historical design standards have become increasingly common, causing severe inundation damage in low-lying paddy field areas. Agricultural drainage systems, particularly drainage pump stations, play a crucial role in mitigating flood damage by removing excess water from farmland and maintaining suitable soil moisture conditions. However, many existing drainage facilities were originally designed based on past hydrological conditions and are operated using conventional management approaches that are inadequate under current climate conditions.

Buyeo County, located in Chungcheongnam-do Province, represents one of Korea's most flood-vulnerable agricultural regions. The area is characterized by extensive paddy fields, low-relief topography, clayey soils with poor drainage capacity, and low river gradients connected to the Geum River basin. During recent extreme rainfall events, prolonged inundation repeatedly occurred despite the operation of multiple agricultural drainage pump stations. In many cases, flood damage was aggravated by insufficient pump capacity, delayed operation, poor coordination among facilities, and the fragmented governance structure between local governments and the Korea Rural Community Corporation (KRC).

Traditionally, agricultural drainage management in Korea has focused primarily on physical infrastructure expansion such as enlarging drainage channels or increasing pump capacity. However, climate change has revealed the limitations of purely structural approaches. Modern agricultural drainage management requires not only improved facilities but also integrated operation, real-time monitoring, predictive management, and coordinated governance.

International experiences suggest that climate-resilient drainage management increasingly relies on decentralized, adaptive, and smart operational systems. Japan has implemented community-based preventive maintenance through the NOSAI agricultural mutual aid system and distributed flood mitigation measures such as Paddy Field Dams. European countries have adopted mobile flood barriers and nature-based solutions to reduce runoff and delay flood peaks. The Netherlands introduced the "Room for the River" strategy, which integrates agricultural land into flood storage systems with strong compensation mechanisms. These international cases demonstrate that resilient agricultural drainage systems require a combination of hardware improvements, natural retention functions, and governance integration.

Against this background, this study aims to analyze the causes of agricultural flooding in Buyeo County and propose an integrated and smart drainage management framework suitable for climate change adaptation. Specifically, the objectives of this study are: (1) To identify the hydrological and operational causes of agricultural inundation in Buyeo County, (2) To evaluate the limitations of existing drainage pump station operation systems, (3) To propose smart and integrated drainage management strategies

for climate-resilient agriculture and (4) To derive policy implications applicable to future agricultural drainage modernization in Korea.

The findings of this study are expected to contribute not only to improving local agricultural flood resilience but also to broader discussions on adaptive agricultural water management under climate change.

2. STUDY AREA AND CHARACTERISTICS OF AGRICULTURAL FLOODING

2.1 Overview of Buyeo County

Buyeo County is located in the western part of Chungcheongnam-do Province, Korea, and is one of the country's major agricultural production areas. Paddy fields account for a significant portion of the cultivated land, and many agricultural zones are situated in low-lying plains adjacent to rivers and tributaries connected to the Geum River system (Figure 1). The region plays an important role in regional food production and agricultural water management because extensive irrigation and drainage networks have been developed to support paddy cultivation over large areas.

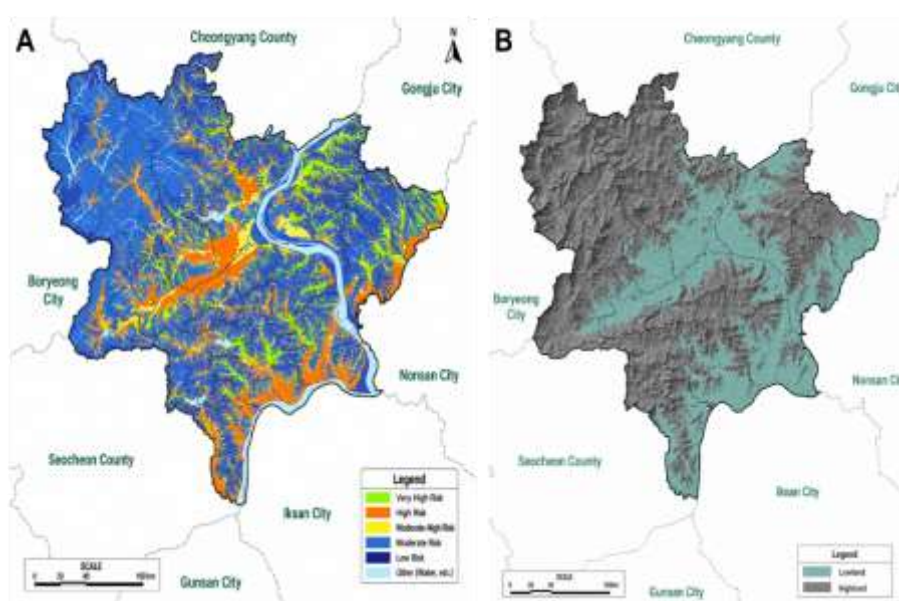


Figure 1. Spatial distribution of flood vulnerability and topographic characteristics in Buyeo County: (A) flood risk classification map showing areas with varying levels of flood vulnerability, and (B) topographic map showing the distribution of lowland and highland areas. The maps indicate that high flood-risk areas are primarily concentrated in low-lying regions along the Geum River basin and surrounding agricultural plains.

The region experiences a monsoon climate characterized by concentrated rainfall during the summer season. In recent years, localized heavy rainfall events exceeding 100 mm within a few hours have become increasingly frequent due to climate change and atmospheric instability. These short-duration, high-intensity rainfall events often generate rapid surface runoff that exceeds the drainage capacity of existing agricultural infrastructure. Because the topographic slope is very gentle, excess rainfall tends to accumulate rapidly in paddy fields and drainage channels, resulting in prolonged inundation and delayed water removal. In particular, flood damage becomes more severe when external river water levels rise simultaneously during heavy rainfall periods.

In addition, the dominant soil type in the area is clayey paddy soil with low permeability. These soils retain water effectively for rice cultivation but significantly reduce infiltration during extreme rainfall events. High groundwater levels, poor subsurface drainage conditions, and limited natural percolation further increase flood vulnerability. Recently, changes in land use, including the expansion of upland

crop cultivation and greenhouse agriculture, have also increased sensitivity to short-term waterlogging in many agricultural areas.

2.2 Characteristics of Agricultural Flooding

Agricultural flooding in Buyeo County exhibits several distinct characteristics. First, flooding is strongly influenced by short-duration intense rainfall rather than seasonal cumulative rainfall. Recent flood events have shown that rainfall intensities frequently exceed the design capacity of drainage systems, leading to rapid water accumulation in agricultural areas (Figure 2). In many cases, rainfall concentrated within only a few hours generates sudden runoff surges that cannot be effectively discharged through existing drainage canals and pump stations. Climate change is expected to further increase the frequency and intensity of such localized heavy rainfall events, thereby increasing future flood vulnerability in agricultural regions.



Figure 2. Representative flood damage cases in Buyeo County caused by extreme rainfall events from 2022 to 2024: (A, B) urban and agricultural flooding in 2022 caused by localized torrential rainfall, (C, D) inundation and greenhouse flooding in 2023 caused by prolonged rainfall and rising river water levels, and (E, F) agricultural land and livestock facility flooding in 2024 caused by concentrated heavy rainfall and stream overflow. These cases illustrate the increasing vulnerability of rural and agricultural areas to climate-induced extreme precipitation events.

Second, inundation duration is a critical factor affecting crop damage. Paddy rice can tolerate temporary flooding to some extent; however, upland crops and greenhouse cultivation systems are highly vulnerable even to short-term waterlogging. Recently, the conversion of paddy fields into upland crop cultivation and greenhouse agriculture has increased flood sensitivity in many areas. In particular,

greenhouse facilities often experience severe economic losses because even shallow flooding can damage cultivation beds, irrigation systems, and electrical facilities.

Third, the drainage system itself has operational limitations. Many drainage pump stations operate independently without real-time coordination. Internal water levels, external river stages, pump operation status, and drainage gate conditions are often monitored separately by different organizations, reducing operational efficiency during flood events. Delayed decision-making and limited information sharing further reduce the effectiveness of emergency drainage operation.

Fourth, sediment accumulation, vegetation growth, and insufficient maintenance in drainage canals reduce effective drainage capacity. Even when pump stations operate normally, reduced conveyance capacity within the drainage network can significantly delay water removal. Insufficient maintenance budgets and labor shortages in rural areas have also contributed to the deterioration of drainage infrastructure over time.

As a result, agricultural flooding in Buyeo County is not simply a hydraulic problem but rather a combined outcome of climatic, topographic, soil, infrastructural, and governance-related factors. These findings suggest that conventional approaches focused solely on increasing pump capacity or expanding drainage facilities may not be sufficient to effectively reduce future flood risks. Instead, improving agricultural drainage resilience requires integrated management strategies that combine real-time monitoring, adaptive operation, preventive maintenance, and coordinated institutional response systems. Furthermore, as climate change continues to increase rainfall uncertainty and extreme weather variability, the importance of data-driven and forecast-based drainage management will become increasingly significant for sustainable agricultural production and rural disaster mitigation.

3. CAUSES OF AGRICULTURAL FLOOD VULNERABILITY

3.1 Climate Change and Extreme Rainfall

Climate change has intensified the occurrence of localized heavy rainfall events in Korea. Meteorological data indicate increasing rainfall intensity and greater variability in rainfall distribution patterns. Traditional design standards based on historical rainfall frequency are becoming insufficient under these changing conditions. In Buyeo County, recent flood disasters have typically occurred during concentrated rainfall events lasting only a few hours. Such events generate rapid runoff exceeding the capacity of existing drainage systems. Moreover, climate change has increased uncertainty in rainfall prediction and timing, making conventional reactive drainage operation less effective.

3.2 Topographic and Soil Conditions

Buyeo County's low-relief topography significantly contributes to flood vulnerability. Because agricultural fields are located near rivers with low gradients, natural drainage is slow, especially during periods of high external river stages. The predominance of clayey paddy soils further aggravates inundation problems. These soils have low infiltration rates and high water retention capacity. During prolonged rainfall, groundwater levels rise quickly, limiting additional infiltration and causing surface ponding. In many converted upland crop areas, drainage systems originally designed for rice paddies are insufficient for crops requiring drier soil conditions.

3.3 Limitations of Existing Drainage Pump Stations

Many drainage pump stations in Buyeo County were constructed decades ago based on historical rainfall conditions and older agricultural practices. Several operational limitations were identified: (1) Pump capacity is often insufficient during extreme rainfall events. Pump operation criteria are usually based on static water level thresholds rather than dynamic rainfall forecasting. (2) Drainage pump stations lack integrated operational control. Internal drainage water levels, river stages, and weather forecasts are not systematically linked. (3) Fragmented institutional management reduces operational efficiency. Agricultural drainage facilities are managed by different organizations, including local

governments and the Korea Rural Community Corporation. Coordination among these organizations during emergencies is often inadequate. (4) Many facilities rely heavily on manual operation and field personnel experience rather than data-driven decision-making systems.

4. SMART AND INTEGRATED DRAINAGE MANAGEMENT FRAMEWORK

4.1 Concept of Smart Drainage Management

Smart drainage management refers to a data-driven operational system integrating real-time monitoring, predictive analysis, and coordinated facility control (Figure 3). Unlike traditional facility-centered management, smart drainage systems focus on operational optimization based on hydrological conditions, weather forecasts, and real-time field data. The proposed framework for Buyeo County includes: (1) Real-time monitoring systems, (2) automated pump operation, (3) predictive flood management, (4) Integrated governance structures and (5) risk-based operational prioritization.



Figure 3. Proposed framework for integrated smart pumping station management incorporating remote control, rainfall forecasting, optimized pump operation, and data integration.

4.2 Real-Time Monitoring and Automation

The first component involves installing real-time sensors for: (1) Internal water levels, (2) external river stages, (3) pump operation status, (4) rainfall intensity and (5) canal flow conditions. These data should be integrated into a centralized monitoring platform accessible to all relevant agencies. Automated pump operation systems can improve response speed and reduce delays during sudden rainfall events. Pumps can be activated automatically based on predefined water level thresholds and rainfall forecasts.

4.3 Forecast-Based Pre-emptive Operation

Traditional drainage operation is largely reactive, starting after water levels rise significantly. However, under climate change conditions, pre-emptive operation becomes increasingly important. By linking pump station management with short-term weather forecasts, operators can lower internal water levels before extreme rainfall occurs. This creates temporary storage capacity within drainage canals and agricultural fields. Pre-emptive drainage operation can significantly reduce peak inundation depth and duration.

4.4 Integrated Governance System

A major limitation of current drainage management is fragmented institutional responsibility. This study proposes establishing an integrated drainage governance system involving: (1) Local governments, (2) Korea Rural Community Corporation, (3) agricultural communities, and (4) emergency response agencies. A shared operational platform and standardized communication protocols are essential for coordinated flood response. Community participation is also important. Farmers can contribute to drainage canal maintenance, local monitoring, and emergency response activities.

5. INTERNATIONAL IMPLICATIONS AND APPLICABILITY

International case studies provide several important implications for Korea. Japan's Paddy Field Dam projects demonstrate how distributed retention systems can reduce flood peaks using low-cost modifications to existing paddy drainage outlets. The Netherlands' "Room for the River" policy shows the importance of integrating agricultural land into broader flood management strategies while ensuring strong compensation systems for farmers. The United Kingdom and United States emphasize nature-based solutions such as cover crops, soil restoration, and runoff attenuation structures to increase infiltration and delay runoff. Japan's NOSAI system highlights the importance of preventive maintenance and community-based cooperation rather than relying solely on post-disaster compensation. These examples indicate that climate-resilient agricultural drainage requires not only infrastructure expansion but also adaptive operation, distributed retention, stakeholder participation, and integrated governance.

6. CONCLUSION

This study analyzed the causes of agricultural flooding in Buyeo County and proposed a smart and integrated drainage management framework for climate-resilient agriculture. The results indicate that agricultural flood vulnerability arises from the combined effects of extreme rainfall, low-relief topography, poor soil drainage, insufficient pump capacity, fragmented governance, and conventional operational practices. To address these challenges, this study emphasizes the need to transition from facility-centered management toward data-driven, integrated operational systems. Key recommendations include: (1) Real-time monitoring and automated pump operation, (2) forecast-based pre-emptive drainage management, (3) integrated governance among relevant institutions, (4) distributed flood mitigation strategies, and (5) community-based preventive maintenance systems. The Buyeo County case demonstrates that operational improvement and governance integration can substantially enhance agricultural drainage resilience even without large-scale structural expansion. As climate change continues to intensify flood risks worldwide, adaptive and integrated agricultural drainage management will become increasingly important. The findings of this study provide practical insights for future agricultural drainage modernization and contribute to international discussions on climate-resilient agricultural water management.

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