

農業灌溉最佳化以提升氣候韌性：結合 AI 與小水力發電實現永續水-糧食-能源管理

Optimization of Agricultural Irrigation to Enhance Climate Resilience: Integrating AI and Small Hydropower for Sustainable Water-Food-Energy Management

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摘 要

近年氣候變遷導致極端降雨與乾旱事件頻率與強度持續上升，嚴重衝擊農業灌溉系統的穩定供水能力。本研究以石門水庫為研究區域，應用非支配排序基因演算法 III (NSGA-III) 模擬不同乾旱情境下灌溉與水庫放流策略，以探討在極端氣候下農業灌溉管理之最佳化策略。本研究比較最佳化方案與原放流操作，並透過標準化水庫蓄水量指標 (SRSI) 評估農業用水效率之提升程度，計算風險緩解成效。同時，本研究從水-糧食-能源 (WFE) 關聯性角度，探討「計畫性配水」與「乾旱指標控制」不同灌溉情境對資源使用效率與環境永續性的影響，並評估整合小水力發電系統整合至灌溉基礎設施之可行性。研究顯示，有效的水資源操作最佳化策略與小水力發電系統之整合，最佳化放流策略可顯著提高乾早期的灌溉效能與水資源調度效率；結合小水力發電則增加能源使用效率。未來在導入即時監測資料與預測模型，可強化系統對極端氣候的快速反應能力，建構兼具韌性與永續發展潛力的農業灌溉管理架構。

關鍵詞：非支配排序遺傳算法 (NSGA-III)，農業灌溉，小水力發電，標準化水庫蓄水量指標 (SRSI) 乾旱管理，水-糧食-能源 (WFE) 鏈結

Abstract

In recent years, climate change has led to increasing frequency and intensity of extreme rainfall and drought events, severely impacting the reliability of agricultural irrigation systems. This study focuses on the Shimen Reservoir region and employs the Non-dominated Sorting Genetic Algorithm III (NSGA-III) to simulate irrigation and reservoir release strategies under various drought scenarios, aiming to optimize agricultural water management in the context of extreme climate conditions. The optimized strategies are compared with the original reservoir operations, and the improvement in agricultural water use efficiency is assessed using the Standardized Reservoir Storage Index (SRSI) to quantify risk mitigation effectiveness.

Furthermore, the study adopts a water–food–energy (WFE) nexus perspective to explore how different irrigation scenarios—namely, "planned water allocation" and "drought index-based control"—affect resource use efficiency and environmental sustainability. The feasibility of integrating micro-hydropower systems into existing irrigation infrastructure is also evaluated. Results indicate that optimized water resource operation strategies and the integration of micro-hydropower can significantly enhance irrigation efficiency and water allocation during drought periods, while also improving energy use efficiency. In the future, incorporating real-time monitoring data and predictive models can further strengthen the system's responsiveness to extreme climate events, contributing to a resilient and sustainable agricultural irrigation management framework. **Keywords:** Non-dominated Sorting Genetic Algorithm III (NSGA-III), agricultural irrigation, small hydropower, Standardized Reservoir Storage Index (SRSI) drought management, Water–Food–Energy (WFE) nexus