結合系統動力學與分岔理論之北關渡灌區農業水資源管理

Agricultural Water Resources Management in the Northern Guandu Irrigation District: An Integration of System Dynamics and Bifurcation Theory

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摘　要

本研究應用系統動力學（System Dynamics）與分岔理論（Bifurcation Theory），於灌溉區域之農業水資源管理，建構灌區水資源供需分析框架，並以農田水利署七星管理處所轄北關渡灌區為案例，研究河川供給水量、灌溉需求特性、及歷年水文資料，以分析不同時期的供水壓力，進一步提出兼具調度與調適功能之管理策略建議。

系統動力學為一套結合系統理論與電腦模擬之量化工具，廣泛應用於農業灌溉、水資源與環境管理等領域，能有效描述複雜系統中各變數間的交互關係與隨時間變化之行為模式。本研究主要貢獻在系統動態中，進行分岔理論之平衡點（equilibrium point）分析，透過平衡點分析，可檢驗此狀態之穩定性。分岔理論探討系統在不確定性狀況下之分岔行為，以建立對灌區水資源系統動態的氣候變遷不確定性之管理策略。

本研究運用系統動力學 Vensim 軟體，建立灌區水資源供需模型與案例分析，模擬水源供給與灌溉需求之動態交互，並評估調控機制對灌溉穩定性的影響。模型除可作為日常灌溉決策支援工具外，亦具備潛在預警與政策分析功能。本研究成果有助於提升農業灌溉管理之科學性、前瞻性與氣候韌性，亦可提供未來推動智慧灌溉、水資源調控及永續農業發展之量化依據。

關鍵詞：系統動力學，農業灌溉，水資源管理、分岔理論

Abstract

This study applies System Dynamics (SD) and Bifurcation Theory to agricultural water resources management in irrigation districts, constructing a supply–demand analysis framework for irrigation water resources. The Northern Guandu Irrigation District, under the jurisdiction of the Seventh Branch of the Irrigation Agency, Ministry of Agriculture, is selected as the case study. By integrating river water supply, irrigation demand characteristics,

and historical hydrological data, the study analyzes water supply pressures across different periods and further proposes management strategies with both allocation and adaptation functions.

System Dynamics, a quantitative tool that combines system theory and computer simulation, has been widely applied in agricultural irrigation, water resources, and environmental management. It effectively describes the interactions among variables in complex systems and their behavioral patterns over time. The primary contribution of this research lies in incorporating equilibrium point analysis within System Dynamics through Bifurcation Theory. Equilibrium point analysis allows for examining the stability of system states, while bifurcation analysis investigates system behavior under uncertainty, thereby providing insights into management strategies for irrigation water resources systems under climate change uncertainties.

This study employs the Vensim software to develop a dynamic supply–demand model of irrigation water resources and conducts a case analysis for the Northern Guandu Irrigation District. The model simulates the dynamic interaction between water supply and irrigation demand, and evaluates the impacts of regulatory mechanisms on irrigation stability. Beyond serving as a decision-support tool for daily irrigation management, the model also possesses potential for early warning and policy analysis. The findings of this study contribute to enhancing the scientific basis, foresight, and climate resilience of agricultural irrigation management, and provide quantitative support for future smart irrigation, water resources regulation, and sustainable agricultural development.

Keywords: System Dynamics, Agricultural Irrigation, Water Resources Management, Bifurcation Theory