

國際灌溉排水協會

《灌溉與排水》期刊精選

氣候變遷下的灌溉水資源永續性與糧食安全

Sustainability of Irrigation Water Resources and Food Security under Climate Change

論文摘要集

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序 言

國際灌溉排水協會（ICID）創立於 1950 年，是一個以科學與技術為核心的非營利國際組織，目前共有 111 個會員國，包含 44 個積極會員國以及 66 個聯繫會員國；該協會長期致力於提升農業灌溉技術與糧食生產效率，近年來關注議題從灌溉排水，逐漸延伸至氣候變遷與衝擊、自然資源管理等層面。我國則於 1969 年以中華民國國家委員會名義加入 ICID，數十年來，穩定發展為我國與全球農田水利專家互動與技術交流的主要窗口。

ICID 每年召開年會並舉辦國際研討會，本會為加深我國對國際灌溉學術與應用趨勢之了解，自 2007 年起彙整並翻譯該年會之重要論文摘要，供國人參考。2020 年時，本會進一步取得 ICID 發行之《灌溉與排水》期刊的中文摘譯授權，系統化傳播國際專業知識；此舉不僅有助於我國農田水利領域接軌國際研究，本會之用心與努力亦獲 ICID 高度肯定。

本年度期刊主題聚焦於氣候變遷對農業水資源的影響，委由 14 位國內農田水利等相關專家學者譯註，共計摘錄論文 33 篇，集結成冊；第一部分關於氣候變遷引發的水資源短缺與永續農業灌溉管理，第二部分探討用水效率提升、乾旱與淹水調適策略，以及非常規水源利用對環境的影響。本會也將配套辦理國際灌溉排水技術成果發表會，除積極探討可供借鏡之道，亦檢視國外措施在臺灣實施之潛在挑戰與可行性。

本集得以發行，實歸功負責譯註之學者專家不辭辛勞，以自身專業智識進行譯註，並提出可供國內政策參考之建言；同時，承蒙行政院農業部農田水利署之指導，財團法人台北市七星農田水利研究發展基金會及財團法人維謙基金會之協助，謹此致謝。本集編纂未盡妥善之處，尚請不吝指正。

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魁北克雨養農業實施灌溉的潛力： 氣候變遷引發的挑戰與調適策略的回顧

Viveka Nand¹, Zhiming Qi²

摘要

由於氣候變遷導致生長季節水分壓力加劇，加拿大東部的氣候變化已擾亂該地區的雨養農業系統。因此，本研究回顧旨在評估魁北克農業地區灌溉現況、氣候驅動下所面臨的挑戰與機會，以及適應策略對經濟回報和環境的影響。儘管目前灌溉主要集中於高經濟價值作物，但有限數量的田區已開始實施具有灌溉功能的控制排水系統（CDSI）。考量未來降雨變異性增大與生長季熱浪事件增加的趨勢，先前研究多聚焦於氣候變遷下的適應實務發展。本研究指出兩項研究缺口：(1) 缺乏對歷史與未來氣候下，乾旱頻率及其對根層土壤水分、作物蒸散(ET)、作物物候及農業生產的區域尺度分析；(2) 缺乏區域尺度的研究探討氣候變遷適應選項（如補充灌溉）及其對經濟回報與水資源可能產生的影響。為發展能保障糧食需求與水資源永續的氣候變遷適應策略，未來研究應進一步填補這些空白。

關鍵字：調適實務、氣候變遷、作物生產、乾旱、灌溉

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註解

本研究探討了在氣候變遷背景下，加拿大魁北克省的雨養農業所面臨的挑戰，並評估了補充灌溉作為調適策略的潛力與其相關的經濟及環境考量。

資料指出，在全球範圍內，雨養農業佔據主導地位，貢獻了至少 60% 的作物生產，並覆蓋約 80% 的農業用地。然而，在全球以及魁北克省，日益增加的降雨變異性與頻繁發生的熱浪，正對雨養農業構成嚴峻威脅。在中度至重度乾旱影響下，即使是短暫的乾旱期，也足以損害作物生產，尤其是在副濕潤地區，且典型的雨養作物產量普遍顯著低於灌溉作物。

目前的研究缺乏在區域尺度下，以歷史或未來氣候情境對魁北克乾旱發生的頻率、及其對土壤水分、作物蒸散量、作物物候和產量影響的全面量化分析；同時缺乏在區域尺度下，對包含補充灌溉在內的氣候變遷調適方案，進行經濟效益及其對水資源潛在影響的評估研究。

填補這些研究空白，對於確保未來糧食供應安全及水資源的永續利用至關重要。

魁北克省擁有豐富的淡水資源，年均降雨量充沛，是大部分農地未採用灌溉的原因，其主要的農業區集中在西南部，且主要作物為玉米和大豆等，而這些作物依賴生長季節的降雨進行耕作，當地的灌溉設施主要用於高經濟價值作物如蔬菜和水果。儘管灌溉總面積相對較小，但在 2010 至 2020 年間呈現增加趨勢。然而，生長季節經常出現短暫乾旱，這對根系較淺的作物（如蔬菜）影響顯著，易導致產量損失。因此，對高經濟價值作物而言，灌溉具有經濟可行性並能提高收益。相比之下，主要作物的根系較深，對短暫乾旱抵抗力較強，實務上較少灌溉，長時間的乾旱仍會導致這些主要作物產量顯著下降。

控制排水地下灌溉 (CDSI) 技術在部分地點的試驗顯示能有效提高玉米和大豆產量，增幅可達 1.3% 至 36.2%，但 CDSI 的普及率不高，主因在於

高昂的安裝成本，而農民是否採用新技術，關鍵取決於預期經濟回報、財務能力及推廣成效，政府補助亦是推動因素。

在過去十年（2012-2021 年），魁北克近期經歷的乾旱事件與全球趨勢一致，特別是中至重度乾旱發生的頻率有所增加，主要集中在生長季節，已造成顯著經濟損失，歷史氣候分析表明魁北克南部農業區的夏季氣溫顯著升高，未來氣候預測指出氣溫將持續大幅升高，夏季升溫尤為明顯。儘管生長季節降雨量預計變化不大或略增，但高溫、熱浪頻繁加上降雨僅微幅增加，將導致夏季出現短期或更長時間的乾旱風險。同時融雪增加和極端降雨事件增多，將增加逕流使土壤及養分流失。

不過氣候暖化也帶來潛在機會，生長積溫的增加預計將延長生長季節，可能為農業向魁北克省北部的擴展提供機會，二氧化碳濃度升高可提高光合作用效率，這對主要作物尤其有利，可能抵消部分暖化的不利影響並增加產量，但這些機會可能同時增加對灌溉用水的需求。

根據各國實務證實灌溉能顯著提高產量，在魁北克省進行的試驗也顯示補充灌溉可提高玉米和大豆產量並增加農民收益。經濟分析表明，高價值蔬菜作物的灌溉投資回本期（1.2 年）遠短於玉米（19.2 年）。擴大灌溉有望提高糧食產量和農民收入。然而，在大規模推行任何灌溉系統前，必須進行全面的經濟與環境影響分析，大規模取水可能對當地水體造成壓力，並引發長期環境問題。評估應優先考量整個流域範圍，而非僅限於單一田塊，同時應探索如雨水收集等替代性水資源管理方案，以確保水資源永續利用。

面對氣候變遷下日益加劇的乾旱威脅，本研究結果顯示灌溉技術具有增產潛力，與魁北克省相同，台灣的年降雨量豐沛，但因地形狹長且高山較多，降雨於地表停留的時間較短，農業仍需仰賴灌溉，未來需要進一步進行灌溉技術的研究，且同時將經濟可行性、環境效益納入灌溉技術實施的評估，以制定有效的氣候變遷調適策略，確保未來的糧食安全與水資源永續性。

摘要翻譯及註解：吳宗聖

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**Potential of implementing irrigation in rainfed agriculture in Quebec:
A review of climate change-induced challenges and adaptation strategies**

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ABSTRACT

Leading to growing-season water stress, eastern Canada's evolving climate has disrupted the region's rainfed farming systems. Accordingly, this review was conducted to assess the status of irrigation, climate-induced challenges and opportunities and the impact of adaptation strategies on economic returns and the environment in Quebec's agricultural regions. While irrigation is limited mainly to high-value crops, controlled drainage with sub-irrigation (CDSI) has been implemented at a limited number of field sites. Given the greater rainfall variability and rising number of growing-season heatwave events anticipated, previous studies have mainly focused on developing climate change adaptation practices. The present study identified two research gaps: (i) a lack of analyses of drought frequency and its effect on root zone soil moisture, crop ET, crop phenology and agricultural production at a regional scale under historical and future climates and (ii) a lack of regional-scale studies addressing climate change adaptation options, including supplementary irrigation, and their potential effects on economic return and water resources under a changing climate. Additional studies must address these gaps for the development of climate change adaptation practices to secure food demand and water sustainability

KEYWORDS

adaptation practices, climate change, crop production, drought, irrigation.

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邁向永續農業水資源管理

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摘要

為了維持地球上生命的存在，食物和水是最基本的需求，沒有這兩者，任何生命形式都無法存活。隨著時代演進，人類社會逐漸依賴穩定的食物供應來確保生存。而食物網中的各種組成，無論是動物產品還是作物，都極度依賴水的供應，以維持其生長與成熟所需的生物過程。當水資源供應因天然或人為原因(如乾旱或缺乏供水系統)而中斷時，食物供應也隨之受到衝擊，受影響的社區將遭受極大的影響。

水是植物生物過程得以持續的關鍵要素，因此農業用水的永續供應至關重要。隨著氣候變遷影響日益加劇，農業水資源的永續性對於確保發展中國家日益增長的人口糧食安全將更加重要。

註解

本文強調農業用水永續管理的重要性，認為水資源是支撐農業生產和糧食安全的核心，尤其在氣候變遷日益嚴重的當下。作者提出永續性不僅取決於水資源的再生能力，也涉及水的來源、使用方式、氣候變化、經濟金融、治理制度與社區參與等多面向因素。水源的多樣性（如水庫、地下水、農田蓄水池等）與其能源足跡密切相關，深深影響水資源利用的永續性。

文中指出氣候變遷加劇了水源不確定性，並增加蒸發與蒸散量，進一步挑戰水資源的穩定。治理與制度、財務資源的充足以及社區的參與與協作，都是實現農業用水永續管理的關鍵。最後，作者建議採取全方位的規劃、動態管理、促進市場與經濟機制、加強社區參與與能力建構，才能邁向真正的永續農業水資源管理。文中指出六大影響永續性的因素包括：

1. 水文特性

水資源因空間、時間、質量的變異，不同於土地或礦物，水的可補充性與區位差異需謹慎評估。規劃者需注重不同水源的可靠性，忽略水源的時空與質變特性，將導致水資源配置失衡，影響長期永續。

2. 水資源來源

水資源來源涵蓋大壩、水庫、集水、地下水、農塘、甚至都市再生水、海水淡化等，水資源的應用需同時評估能源消耗與其經濟性，因此能源足跡對水源可持續性有很大的影響，而再生能源在大型水源開發應用的限制下，未來發展潛力值得深入探討。

3. 用水用途

作物種植模式改變影響需水量，易導致用水壓力與區域不均。用水轉型會帶來的社會與資源分配不均（如上游水量充足、下游水量不足），是許多灌溉區的共同困境，需用制度規範與技術支持（提升用水效率）預防。

4. 氣候變遷

氣候變遷加劇水資源時空不均，增加蒸發、蒸散損失，要求更大的儲水與調配彈性。而氣候變遷不再是未來式，各項工程設計需即時納入氣候適應與減緩衝擊的方案，如韌性設施與智慧管理等。

5. 經濟、財務與治理

公共部門須負擔治理與公平調配，財務不足會導致「建設-忽略-重建」循環。制度與財務可持續性的缺失，是許多發展中國家水資源管理的致命傷，治理創新與財務永續方案（如用水者付費、PPP 模式）均須於計畫規劃初期就予以考量，並同時推動。

6. 制度與社群

永續管理需制度化治理與社區參與，提升民主與協作能力。社區與水利會的參與是永續關鍵，但現實中地方能力不足、政治介入仍是挑戰，需從制度設計與能力培育雙管齊下。

本文系統整理了農業水資源永續管理的挑戰與路徑。農業用水的管理絕非單純的水源開發與灌溉技術問題，而是一個涵蓋自然科學、經濟、社會與治理的綜合性議題。面對氣候變遷的影響說明，未來必須強化適應氣候變遷的管理配套策略，例如水源的多元開發、智慧灌溉與能源效率的提升等。文中特別提出對於社區參與與治理制度的重視，因為沒有地方參與與制度保障，再好的水資源計畫也難以長久。這也對規劃水資源政策時，提供了更全面的視角。台灣水資源面臨極端氣候與分布不均的挑戰，本文的分析對於台灣思考農業水資源的永續策略，非常有啟發性，尤其是針對公部門在農業水資源開發計畫所扮演的角色與私部門用水管理能力的提升，均有很深刻的剖析。

摘要翻譯及註解：張煜權 教授

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Towards sustainable agricultural water management

Ashwin B. Pandya

ABSTRACT

For sustaining life on this planet, the food and water are the prime requirements without which any of the life forms are not able to survive. Over the period of time, the human society has started depending upon the assured food supplies for ensuring their sustenance. The components of the food basket be they animal products or crops, depend heavily upon the availability of water to sustain their biological processes for growth and maturity. Whenever we see disruption in the water supply due to natural or artificial causes like drought or nonprovision of water supply systems, we find the disruption in food supplies and enormous sufferings for the communities affected.

Water being the key ingredient for sustenance of the biological processes in the plants, sustainability of the water supplies for agriculture has assumed great importance. With the increasing effects of climate change, this aspect will assume further importance in ensuring food security to the growing populations across the developing world.

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印度具氣候韌性的水資源基礎建設

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摘要

印度每年降水量約為 3880 億立方公尺，而平均可得水量則為 1999 億立方公尺。受地形限制、水資源分佈等因素影響，實際可利用的水資源僅為 1126 億立方公尺。在印度，農業仍為約 54.6% 人口的主要生計來源。2010 年印度全國的總用水需求估計為 710 億立方公尺，其中灌溉用水約為 557 億立方公尺，占總用水的 78%。由於可用水資源有限，無法滿足各部門的水需求，預測至 2050 年，印度的總用水需求將達到 1180 億立方公尺，超過目前 1126 億立方公尺的可利用水資源。此外，全國多個地區的地下水位正以令人擔憂的速度下降。此外，氣候變遷對各個生活與經濟領域構成重大且深遠的威脅。降雨模式日益不穩定，顯著加劇了印度境內洪水與乾旱的發生頻率。本研究旨在探討氣候變遷對水資源各層面所造成的影響，強調發展與投資氣候韌性水資源基礎建設的必要性，並闡述印度政府在此方向上所推行的行動。

關鍵字：氣候變遷、地下水、處理廢水再利用、水與糧食安全、水資源保育、水資源基礎建設

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註解

氣候變遷所帶來的水資源壓力是許多國家都面臨的問題，而氣候變遷對水資源基礎建設的五大影響包含水文變異性增加、冰河融化增加、水質劣化、降低地下水補注與海平面上升，這些都將衝擊水資源基礎建設的規劃、設計與管理。本研究所指涉的水資源基礎建設範疇包含水庫、灌溉渠道系統、地下水、河川治理、都市排水、自然水體、廢水處理與防洪設施。作者提出建立具氣候韌性的水資源基礎建設的十二項要點，包含 1)研究與發展、2)檢討既有政策指引、3)以實證為基礎的政策、4)財務、5)提升大眾意識、6)人才培育、7)跨洲際合作、8)提升蓄水能力、9)節水與用水端管理、10)最大化科技使用、11)整合性水資源管理、12)自力更生創新。

在水壩管理上，由印度中央水利委員會主導的「水壩復建與改善計畫 (DRIP)」欲提升全國老舊大型水壩的結構安全、操作效率與管理能力。該計畫之工作內容包含進行水壩健康評估、實施修復與加固工程、安裝監測儀器、制定緊急應變計畫，建立安全指引等。印度政府也在 2021 年頒布《水壩安全法》，所有大型水壩需依該法進行監測、檢查、操作與維護，以確保水壩的安全運作。印度的灌溉渠道系統所面臨的問題為系統維護不良、漏水與蒸發損失、盜水與漫灌盛行，故因應之措施包含改善操作與維護、加強更新與現代化及推廣節水灌溉措施(如滴灌與管路灌溉)。印度地下水資源保育的最大挑戰為農業用水的過度抽取。聯合國的調查資料指出，印度農業地下水的用量占了全球 26% 的地下水抽取量。為改善地下水管理，印度的 Atal Bhuja Yojana 計畫以水資源緊張區域的地下水管理為標的，著重社區參與及以需求端為導向的介入措施。該計畫之目標包含地下水相關資訊的公開揭露、由社區主導訂定水資源安全計畫、對核准的水資源安全計畫提供公共財政支持、推廣效率用水的實務措施與改善地下水條件。此外，為更加了解地下水資源狀態，印度於 2012 年啟動全國含水層調查與管理計畫。透過地質、地球物理、水文與化學的實地與實驗室分析，評估含水層中的地下水儲

量、品質與永續性。

印度政府的水資源保育行動可分為雨水收集、流域發展計畫與池塘活化三個部分。在廢水處理與再利用上，國家潔淨恆河任務(National Mission for Clean Ganga)為全國性的廢水處理再利用的指導架構，鼓勵經處理廢水與污泥的再利用。電力部、農業部與鐵道部透過簽署合作備忘錄的方式共同推動處理污水再利用。根據能源部 2016 年電價政策的規定，火力發電廠必須使用半徑 50 公里內公家污水處理廠所產出的處理後污水。在全球氣候變遷的背景下，台灣有部分的水資源基礎設施與印度遭遇類似的問題，如水庫老化、灌溉系統維護、過度抽取地下水、各用水部門用水競爭等。由於台灣高度依賴水庫供給民生與產業用水，水庫淤積或久旱不雨皆會造成慢性與急性的用水緊張。我國政府除持續進行水庫清淤、優化水資源調度系統外，也積極推動科技造水(如再生水、海水淡化廠)，降低對水庫的依賴。113 年實施之「開發單位使用再生水辦法」，更明定計畫用水量達每日 2 萬噸以上的開發單位，其工業用水須使用至少 50%系統再生水。

目前台灣最具上位性的水資源政策為行政院於 110 年 8 月核定之「臺灣各區水資源經理基本計畫」，該計畫盤點我國水資源待改善問題及因應對策，並以維持供水穩定、加強供水韌性及改善供水環境為三大目標，在推動工作上，則以「流域整體經營管理」、「打造西部廊道供水管網」及「強化科技造水」為三個經營主軸，並以「管理」、「節流」、「調度」、「備援」、「開源」為對應之 5 大經理策略。在開源上，我國之主要政策以興建海水淡化廠、發展廢水再生/再利用與開發伏流水為主，其性質仍不脫集中式管理之思維，然而或許可納入分散式管理的想法，考慮以村里、社區、家戶為單位的群體是否有獨立收集並產生可飲用水的能力，並投入資源進行研發工作。

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Climate-resilient water infrastructure in India

Kushvinder Vohra, Saurabh

ABSTRACT

India receives an annual precipitation of about 3880 BCM and the average water availability is 1999 BCM. Out of this, utilizable water resources are 1126 BCM due to topographic constraints, distribution effects and so forth. In India, agriculture remains the principal source of livelihood for about 54.6% of the population. The overall water demand of the country in 2010 was estimated at 710 BCM, of which the water use in irrigation was about 557 BCM (78%). With limited water resources available for fulfilling the water requirement of all the sectors, it is projected that by 2050 our overall water demand (1180 BCM) would outgrow the total utilizable water resources, namely 1126 BCM. Moreover, the groundwater table in various regions of the country is seeing a decline at an alarming rate. Additionally, climate change poses significant and far-reaching threats in all spheres of life and the economy. The erratic rainfall pattern makes a significant contribution to the frequent occurrence of floods and droughts in the country. This paper attempts to put in context the impact of climate change observed on various facets of water resources, the need to develop and invest in climate resilient water infrastructure, and to highlight several initiatives taken by the government of India in this direction.

KEYWORDS

climate change, groundwater, reuse of treated wastewater, water and food security, water conservation, water infrastructure

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氣候韌性灌溉：

實現宜居星球下平衡糧食生產與水資源安全的關鍵轉型

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摘要

具氣候韌性的灌溉系統是永續發展的必要條件，並與減少貧困、糧食安全與環境保護等更廣泛目標相契合。透過調適策略與共同協作，各地社區使得因應氣候變遷所帶來的挑戰，進而保障生計與生態系統。

具氣候韌性的灌溉系統透過強化農業，提升社區的因應能力與整體韌性。農業、灌溉、水資源與氣候變遷之間的相互關係，促使傳統灌溉需轉型為更具氣候韌性的灌溉方法，例如：由農民主導的灌溉發展、創新與現代化以確保灌溉系統與基礎設施的長期可行性與功能性、支持邁向氣候韌性的融資機制、有效動員資源的政府、國際組織與私人部門間的夥伴關係，以及促進水資源的公平取得與有效管理的高效的服務提供機制。

本文強調氣候韌性灌溉在糧食生產與水資源安全之間達成平衡的必要性，主張需進行水資源永續管理的典範轉移，以確保在面對氣候不確定性時的系統韌性，同時維護農業生產力與環境完整性，打造宜居的地球。

關鍵字：農業、氣候韌性灌溉、發展效益、農民主導的灌溉、融資、灌溉與排水、服務交付、永續、轉型、願景、水資源安全、女性

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註解

「氣候韌性灌溉」(climate-resilient irrigation, CRI) 作為減少貧困、糧食安全、環境保護與水資源永續的整合解方，需轉向以服務交付 (service delivery) 與系統性治理為核心，整合科技創新、性別平權、在地小農參與與多元融資機制，建構更具適應力之農業用水系統。

在氣候變遷下灌溉發展的轉型下，灌溉和排水系統應從單一工程導向走向整合性服務導向，本研究強調新型態的策略需顧及三大面向，以期投資、機構和決策方面取得更好的成果，以提高灌溉的效益。三大面向包含：治理、水會計與審計和向客戶提供有效的服務（治理與客戶導向服務、永續利用水資源）、支持私人農民主導的灌溉發展和增強婦女權能（小農與婦女、性別與平等）、基礎設施創新和現代化以及融資（創新與現代化、多元化融資途徑）。

在治理、水會計和向客戶提供有效的服務方面，強調學習其他服務業的作法，強調契約與問責制度，確保服務品質，轉而強調服務品質與回應性。為確保在氣候變遷下水資源供應的穩定性，灌溉服務機構將納入最新技術支持灌溉治理、規劃與管理，討論內容超脫於灌溉效率、官僚體制和僵化的輪作制度，回歸對水平衡、服務交付績效的衡量與基準化進行探討，並確保當地可利用的水資源範圍內，生產現在和將來所需的糧食。此外，透過遙測技術所獲得的資訊，有助於提供透明且負責任的決策管理方案，同時兼顧環境水平衡與用水者的需求，以確保糧食安全和維持農村生計。

在支持私人農民主導的灌溉發展和增強婦女權能方面，研究指出小型農戶與女性農民實際上佔據農業社群的組成與產值相當大的部分，因此需採取自下而上的機制以確保包容性發展，例如農民可透過自主或集體推動灌溉投資、技術創新與市場鏈結，同時政府需在政策上有所調整以協助小農與婦女改善生計並促進灌溉產業發展。此外，女性農民普遍面臨資源與資訊取得上的不平等，故須制定相應的政策，同時促進婦女參與灌溉系統管理，

有助於提升農業體系的包容性與韌性。

在基礎設施創新和現代化以及融資面向，本研究強調灌溉與排水系統面對氣候變遷所帶來的挑戰時，創新與現代化是提升系統效率與韌性的關鍵。灌溉系統須具備精準可控與靈活調度的能力，以因應水文條件日益不穩的情境。同時，在面對龐大的基礎建設資金缺口下，需由政府主導轉向涵蓋多元來源的融資模式，例如引入私人與農民資金、強化灌溉計畫之成本回收機制（如關稅與稅費）等，以確保灌溉系統的永續經營與財務穩定。

本研究與台灣之智慧灌溉系統屬同質性之研究，現行研究尚集中於技術層面，但在制度創新、性別與弱勢群體參與、灌溉服務契約化、與多元融資等面向仍顯不足。氣候韌性灌溉不應僅限於技術導入，而需更全面地回應水資源治理、社會參與與農業轉型的制度性課題。除了呼應聯合國 SDGs 標的外，在技術導入上，應嘗試融入以自然為本解決方案的精神，確保生物多樣性的自然正向發展，與結合環境治理的 ESG 精神。台灣可參照國際經驗，建構兼具永續與彈性的在地灌溉政策。

摘要翻譯及註解：許少瑜 教授

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Climate-resilient irrigation: Essential changes to balance food production and water security on a livable planet

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ABSTRACT

Climate-resilient irrigation is a necessity for sustainable development, aligning with broader goals of poverty alleviation, food security and environmental stewardship. By embracing adaptive strategies and fostering collaborative efforts, communities can navigate the challenges posed by a changing climate, safeguarding livelihoods and ecosystems. Climate-resilient irrigation can improve coping measures and build resilience for communities through pathways which help improve agriculture. The relationship between agriculture, irrigation, water resources and climate change calls for an evolution of traditional irrigation practices towards climate-resilient irrigation approaches, such as farmer-led irrigation development; innovation and modernization to ensure the long-term viability and functionality of irrigation systems and infrastructure; financing mechanisms to support the transition towards climate resilience; partnerships between governments, international organizations and the private sector to mobilize resources effectively; and efficient service delivery mechanisms, promoting equitable access and effective management of water resources. Emphasizing the need climate-resilient irrigation to balance food production and water security, this essay advocates a paradigm shift towards sustainable water management, ensuring resilience in the face of climate uncertainties while safeguarding agricultural productivity and environmental integrity for a livable planet.

KEYWORDS

agriculture, climate-resilient irrigation, development outcomes, farmer-led irrigation development, financing, irrigation and drainage, service delivery, sustainable, transformation, vision, water security, women

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非洲糧食問題與土地利用覆蓋、灌溉採用和水資源短缺之關聯

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摘要

本研究探討非洲水資源短缺、土地利用與覆蓋變化，以及灌溉技術的採用，與該地區糧食問題之複雜關聯性，補足過去文獻對於先前關於非洲糧食安全如何受到土地利用不當及水資源可得性影響的研究之不足，以提升農業生產力，資源管理與政策。本研究透過量化與質性研究探討問題：非洲的糧食不安全與水資源短缺之關聯；灌溉系統在非洲糧食安全中扮演角色；土地利用與覆蓋如何影響非洲的糧食供應。

由於農民獲得的水資源計畫使用效率低，政府運作效能不彰及水資源管理不善，導致農業生產力下降。雨養農業系統面臨不利，使許多小農未積極投入灌溉。本研究結果顯示，非洲的糧食問題與水資源短缺相關，在乾旱、旱季及乾旱地區對農業生產力構成嚴重障礙，因此在水資源匱乏地區，加強灌溉並改善土地管理是提高生產力的必要措施。透過小型灌溉系統或旱季種植高價值作物、實現多季種植或保護作物免受不穩定降雨風險，來提升農業產量，以因應糧食問題。土地利用與覆蓋的變化對非洲的糧食供應亦有顯著影響，不當的土地利用和缺乏保育措施導致可耕地日益缺乏及農場規模縮小，影響農村家戶的糧食安全，應予以規範。

關鍵字：非洲、氣候變遷、糧食問題、灌溉系統、土地利用、水資源可得性

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註解

一、研究背景與核心議題

非洲糧食問題是一個長期且複雜的挑戰，其根源涉及自然環境、社會經濟、技術水平及政策制度等多個層面。過去研究顯示非洲農業產量低、生產效率不高、糧食進口依賴度高，以及農用資材未能有效利用，是導致非洲許多國家長期面臨糧食短缺和營養不良困境的主要原因。

本研究核心目標在於其關鍵環境與農業實踐因素包含水資源短缺、土地利用與覆蓋的變化，以及灌溉技術的採用與糧食不安全之相關。由於氣候變遷的影響、資源整體利用效率以及灌溉技術的推廣對於糧食生產的重要性已獲得普遍認同，但過去文獻在諸因素如何共同作用並影響糧食問題方面著墨不多，因此，本研究採用量化數據分析和質性案例研究成果進行全面系統性評估方法，探討關於非洲糧食安全與灌溉的實際應用、土地利用方式及其地表覆蓋變化，與水資源利用之間關聯性，以降低農民對雨養農業的依賴，透過探討有效資源利用、評估生產力，降低農民糧食匱乏，從而對現有水資源措施有所貢獻。

二、非洲的糧食問題與水資源、灌溉決策之影響

非洲的糧食安全狀況嚴峻，持續依賴進口，國內生產無法滿足需求，源於農作物生產力低下、改良投入物利用率不高，以及小農普遍面臨傳統低效技術、資源獲取困難和農場規模過小等問題。為提升農業生產力，需要增加現代投入與技術應用、優化現有資源配置，解決相關的社會經濟及制度性障礙。因此，擴大灌溉覆蓋和改善土地利用是促進農業可持續發展與提升產量的關鍵。

許多研究已揭示氣候變遷對非洲農業產量及糧食安全的負面影響，而水資源短缺之衝擊較少受到關注。非洲農業其顯著特點是其對自然降雨的高度依賴，即所謂的雨養農業，該生產方式使得該地區的作物產出極易受到氣候波動，特別是降雨量和降雨模式變化的直接影響，從而使其在面對糧食

不安全的衝擊時顯得尤為脆弱，外加非洲面臨多重水資源挑戰：水量不足與水質不佳、水資源基礎設施匱乏及欠缺投資水資源決策，導致水資源利用效率低下且浪費嚴重，對小農生計構成威脅。政府水資源計畫的不足、行政效率低下和管理不善，進一步削弱了農業發展潛力。可用水資源水量質直接影響糧食安全水平，且氣候變遷和人口增長預期將加劇水資源供需矛盾，迫使現有農業體系必須強化水資源管理和提升用水效率。

面對乾旱和土壤缺水造成的產量損失，適應性灌溉系統成為必要的應對措施。灌溉農業的產量預期高於傳統雨養農業，其為增強糧食安全和抵禦乾旱的關鍵策略。由於資金、地理位置（遠離水源）等因素，許多小農尚未有效採納灌溉系統，灌溉系統對非洲應對降雨高度變異性、穩定並提升農業產出至關重要，同時能帶動就業、緩解季節性食物短缺，促進作物多樣化。小型灌溉系統在提升地方糧食安全和農業生產力方面展現出巨大潛力，故擴大灌溉規模並優化水資源管理，是水資源匱乏地區增產的核心途徑。

儘管灌溉潛力巨大，非洲灌溉農業的發展卻相對遲緩，多數灌溉技術的採用率不高，使得易受糧食不安全影響的弱勢群體的處境未能得到顯著改善，灌溉項目推廣受阻原因包括項目規劃規模不當、氣候變化帶來的額外風險、政治因素的干擾以及管理體系缺陷。技術採納與否受社區既有社會規範的影響，而資金短缺、設施維護不到位、農民技術支援服務的缺失以及農戶自身經濟能力有限，是小農灌溉系統普遍面臨的管理難題。農民文化觀念也影響灌溉技術的接受程度，任何技術創新的成功，不僅取決於其實際效益，也取決於潛在使用者如何認知和評價，和其所處社會文化環境是否有利於接納變革。市場便利性、信貸的可獲得性、灌溉設備供應狀況與小農群體間資訊流通和媒體宣傳，都是影響灌溉技術能否順利推廣重要外部因素。

三、非洲的糧食問題與土地利用、覆蓋之影響

在非洲許多地區，可用土地日益缺乏，平均農場規模已逐漸縮小，土地取得受限日益被認為是阻礙非洲農村家戶糧食安全的一個問題，其影響土地利用變化的兩個主要因素為農業和人口。在非洲人口稠密的地區，耕地限

縮，農場規模狹小，糧食不安全問題預計將惡化，氣候變遷對土地利用、生產力有其影響，土地的生產力降低進一步促使土地利用的轉型。不當的土地利用變化和缺乏保育措施被認為是導致糧食安全的土地利用和土地覆蓋變化的可能原因。

研究採用 2000 年至 2018 年非洲四個區域之面板數據（次級資料）進行評估並量化長期土地利用與覆蓋對作物產出之衝擊分析。作物生產以指數衡量，作為應變數；解釋變數為假設影響作物生產之土地利用與覆蓋要素，包括灌溉地、可耕地及林地。研究採用動態模型檢視長期土地利用與覆蓋對作物產出之衝擊，並透過迴歸變數之落後值及方程式層級之工具變數來處理內生性問題，捕捉區域性問題及特定時間效應。其作物生產作為應變數，影響作物產出之土地利用與覆蓋面向則為解釋變數。

實證結果顯示，廣義動差估計法（GMM）似乎更適合用於動態估計方法，灌溉與可耕地對農業生產有正向且顯著的影響，當解釋變數之係數為正時，農業產出上升；當係數為負時，則下降。因此，在所有其他投入保持不變的情況下，灌溉地和可耕地每增加 1%，分別導致農業生產增加 0.95% 和 0.42%。此結果與過去文獻之實證一致。

四、政策意涵與未來方向

非洲的糧食不安全是由水資源短缺所造成，這在乾旱、旱季及乾旱地區對農業生產力構成嚴重障礙，而氣候變遷及可用水量減少促使雨養農業系統日益脆弱。本研究提出的核心政策建議是將增加灌溉投入、擴大灌溉面積作為一項優先策略，推動農業生產的整體增長，緩解和降低區域性的糧食不安全風險。

為確保水資源的開發利用能夠真正惠及目標群體並實現可持續性，研究建議必須將各個層級的利益相關者的廣泛參與水利發展和水資源管理工作，包含基層農民用戶組織、地方社區代表、區域性的水務規劃部門、國家級的政策制定機構，乃至相關的國際發展夥伴和非政府組織。通過多方協商、共同決策的治理模式，實現水資源的公平、高效和可持續利用，以降低

非洲糧食問題。

摘要翻譯及註解：賴家茜

國立清華大學環境與文化資源學系

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Is Africa's food insecurity linked to land use coverage, irrigation adoption and water scarcity?

Yadeta Bedasa

ABSTRACT

The low agricultural yield and production in Africa, ongoing food insecurity and ineffective use of farm inputs are the main motivations for this study. Hence, to increase agricultural productivity, fundamental adjustments to resource management and policy are needed. However, there has been little prior research on how Africa's food security is affected by inadequate land usage and water availability. As a result, farmers are given access to insufficient water projects, which lowers agricultural productivity due to ineffective government operations and poor water resource management. Despite many unfavourable changes to their rainfed agricultural systems, many smallholder farmers have not embraced irrigation investment. The results of this study indicated that more irrigation and better management of land were required to increase productivity in water-scarce areas. The acceptance of irrigation by farmers greatly depends on their social and cultural knowledge, their participation in new projects, methods and technologies, as well as their capacity to adapt. The key policy implication is an increase in irrigation in an effort to boost agricultural growth and reduce food insecurity. It is advised that the participation of stakeholders, planners and policymakers at all levels is the foundation of water development and management.

KEYWORDS

Africa, climate change, food insecurity, irrigation, land usage, water availability

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制度多樣性在永續水資源使用中的角色： 水資源使用組織績效比較

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摘要

本研究旨在比較農業部門中不同類型水資源使用組織(Water User Organizations, WUOs)之管理績效。研究以土耳其孔亞封閉流域為對象，透過問卷調查蒐集 67 個 WUOs 資料，涵蓋灌溉合作社、地方政府、村落法定機構(Village Legal Entities, VLEs)與水資源使用協會(Water User Associations, WUAs)。本研究依據多項指標構建管理績效指數(Management Performance Index, MPI)，進行全面評比。結果顯示，地方政府在物理績效方面表現最佳，灌溉合作社於經營與社會績效中具優勢，而 WUAs 則於制度與投資層面表現最為出色。綜合管理績效指數顯示，孔亞封閉流域中表現最優異的 WUOs 為 WUAs。因此，研究建議其他組織參考 WUAs 之制度化經驗，推動治理改革。此外，亦建議採行預付費制度以減輕收費困難，水價應依「完全成本法」(Full Cost Pricing)計算。最後，推動替代能源於灌溉系統之應用亦為關鍵策略之一。

關鍵字：灌溉水資源管理、管理績效指數、組織績效、水資源使用協會

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註解

本研究從制度多樣性的視角出發，深入探討土耳其孔亞封閉流域中四種類型水資源使用組織(WUOs)在農業灌溉管理上的績效表現。該區為土耳其水資源最為緊張之地，灌溉需求高度集中，具高度代表性。研究涵蓋 67 個 WUOs，類型包括灌溉合作社、地方政府、村落法定機構(VLEs)與水資源使用協會(WUAs)。透過問卷與實地訪談，蒐集各組織在行政管理、財務營運、設施使用效率與社會影響等多方面資料。

為系統性比較不同制度型態之管理表現，研究團隊建立「管理績效指數」(MPI)，涵蓋五大面向：物理績效(如灌溉率與設施運轉率)、經營績效(如收費效率與營運支出)、制度績效(如人力使用密度與治理架構)、投資績效(如設施回報率與單位產值)以及社會績效(如農戶收入與貧窮緩解效果)。各項指標標準化後整合為綜合分數，便於比較各類 WUOs 的整體與分項表現。

研究結果顯示，各類組織的管理重點與績效表現差異明顯。WUAs 於制度設計最為成熟，具有明確權責劃分與使用者參與機制，展現出卓越的人力效率與投資報酬，且能有效運用有限資源達成高效服務；灌溉合作社雖制度化程度相對較低，卻因與農民社群緊密連結，在財務自足與回應農戶需求上具有優勢，尤其表現在農戶福祉與費用收繳表現；地方政府依賴公部門穩定預算與技術資源，在基礎設施維護與供水穩定方面表現突出，但在人力與成本配置上則顯不足，整體靈活性較低。

在財務制度方面，研究特別提出應推動全面採行「完全成本法」，即在訂定水價時納入所有直接與間接成本，包括抽水、維護、人事、資本折舊、行政管理與環境外部成本(例如水源枯竭與污染治理費用)。此一計價方式不僅可反映水資源的真實價值，有助於減少浪費行為，也有助於提升財務透明度與促進使用者對灌溉系統的責任認同。目前多數 WUOs 仍採面積或作物類型收費，忽略實際用水差異與設施壓力，導致財務赤字與公共資源低效配置。搭配預收費制度與區段化管理，完全成本法更可有效解決收費不均與資源耗損問題。

制度設計對於 WUOs 的永續營運與治理績效具有根本性影響。研究結果指出，自主治理能力、合理費率機制、使用者參與程度與投資誘因，是影響績效差異的關鍵因素。此一整合式評估架構與實證結果，為全球水資源治理提供可量化、可操作的政策參考依據。

本研究的發現對臺灣當前農業灌溉制度改革具有高度參考價值。自 2020 年農田水利會改制為農田水利署後，臺灣灌溉管理體系進入官辦導向的新階段，如何在公部門架構中維持組織效率、財務平衡與使用者參與，是當前迫切面對的挑戰。以下為對臺灣的具體建議：

1. 推動多元治理試點計畫

建議在彰化、雲林、台南等具有地方管理經驗的區域，導入仿 WUAs 模式的使用者參與治理制度，建立公私協力的示範單位，彌補官僚體制對在地需求的遲鈍與回應不足。

2. 建立績效導向的灌溉評估制度

參考 MPI 架構，臺灣可建立涵蓋供水效率、成本回收、人力使用與社會效益的績效評估工具，作為經費分配、人力配置與組織調整之依據，促進治理透明與制度進步。

3. 強化使用者付費與預收費機制

仿效 WUAs 以預收費結合完全成本法，有效提升費用回收與用水者的責任意識。臺灣應推動差異化水價與流量計費制度，建立財務可持續與行為誘導兼具的收費機制。

4. 優化人力與組織配置彈性

WUAs 成功在於高度人事自主與任務導向的彈性運作。臺灣水利署可試行分區專責團隊制，賦予基層組織更大的決策權與調度空間，以因應多變的水資源挑戰。

5. 發展永續與智慧水資源技術

鼓勵發展替代能源灌溉技術(如太陽能抽水系統)，並導入 IoT 水位感測 (IoT-based water level sensing)與雲端水資源管理平台，提升灌溉系統調

度效率與氣候適應能力。

總體而言，本研究提供一套可操作的制度比較方法與實證證據，支持導入績效導向與使用者參與的水資源治理模式。對臺灣而言，在氣候變遷、水資源緊張與農業轉型交織的壓力下，建立制度彈性與效率並重的灌溉管理體系，將是實現永續農業與區域發展平衡的關鍵所在。

摘要翻譯及註解：許舒涵 助理教授

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**The role of institutional diversity in sustainable water use:
Performance comparison among water user organizations**

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ABSTRACT

The aim of this study was to compare the performance of water user organizations (WUOs) in the agricultural sector in terms of their managerial efficiency. A survey was carried out across the study area to evaluate 67 WUOs, including irrigation cooperatives, municipalities, village legal entities (VLEs) and water user associations (WUAs). The findings were then used to create a management performance index. It has been determined that municipalities excel in terms of physical performance, irrigation cooperatives in enterprise and social performance and WUAs in institutional and investment performance. The general management performance index revealed that the most successful WUOs in the Konya closed basin were WUAs. Therefore, proposals have been put forward to begin institutionalization processes in other institutions to attain the successful institutionalization in WUAs. Additionally, the shift towards prepaid systems is recommended to mitigate collection problems, while water should be priced according to the full cost method. Finally, supporting the use of alternative energy sources for irrigation is crucial.

KEYWORDS

irrigation water management, management performance index, performance of the associations, water user associations

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農業水資源管理達永續發展目標所需之研究與發展

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摘要

聯合國呼籲行動，以實現 17 項永續發展目標 (SDGs)。本文認為目前的發展典範阻礙了部分永續發展目標的達成。此研究提出 14 項農業研究與發展的需求，以實現這些關鍵目標。此文亦指出，若要能推動上述研究與發展並看到執行之成果，需有全球與國際組織的典範轉移。重要的是，全球北方國家必須調整過去專注於確保便宜土地、水資源與勞力以發展農業出口，為北方投資者創造商機這樣的發展重心，轉向創造機會給予當地農業社群，使其能為當地市場生產糧食、提升收入，並產生在地就業與商業機會。循環型糧食系統可促進多項永續發展目標的實現，如消除飢餓、終結貧窮，並減緩人口遷移，特別是青年遷徙至大城市或海外尋找不穩定工作的情況。

關鍵字：農業水資源管理、糧食不安全、全球南方、研究與發展、永續發展目標

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註解

本文為研究者在執行 2013 至 2023 年，由澳洲國際農業研究中心出資的“南部非洲小型灌溉轉型專案”(Transforming Small-Scale Irrigation in Southern Africa (TISA)經驗中所衍伸出的建議。研究者指出目前在實現永續發展目標上，尚需要 14 項研究與發展重點及對應的 4 種典範轉移。研究者呼籲之研究與發展重點可分為非技術層面(1 至 8)與技術層面(9-14)兩種。

1. 衡量與評估農業生產的適宜性：除了以遠端探測技術或經濟方法計算市場價值外，應納入農業部門滿足在地糧食與營養需求、促進地方經濟發展以及減少對生態系統衝擊等方面的能力。
2. 農業與灌溉為複雜糧食生產系統的一部分：需運用系統思考的方法促進轉型變革，建立具功能且可獲利的生產系統。
3. 農民需有選擇作物與用水管理的自主性：管理結構需使農民能反應市場訊號，自主選擇種植作物，並根據作物需求管理水資源供應。
4. 農民需與市場連結並獲利-1：藉由整合農業與在地企業，實現價值加值、經濟發展與創造就業機會，
5. 農民需與市場連結並獲利-2：確保最大價值能保留於在地經濟中並將發展重點從提升產量轉為提升利潤，並發揮所有可利用農業產出的最大經濟價值。
6. 整合的生產系統：需有整合雨養農業(rainfed)、灌溉農業與畜牧業之產出的措施，以最大化三者之間的有益協同效應(beneficial synergy)。
7. 使發展計畫與在地、區域及國家層級的發展願景保持一致-1：需有國家與區域層級的農業規劃與程序，以確保政府僅接受那些有助於國家經濟發展、支持貸款償還並確保長期永續性的提案。
8. 使發展計畫與在地、區域及國家層級的發展願景保持一致-2：設計與執行捐助者與 NGO 組織的介入項目時，應確保：(i) 整合在地利害關係人，並使在地社群擁有計畫的主導權；(ii) 計畫設有從實施階

段過渡到永續營運階段的機制，並讓私部門在其中扮演重要角色。

9. 與在地利害關係人合作發展農業技術：由在地居民自行開發或合作研發具成本效益且永續的農業技術與措施，提升小農對市場變動與氣候條件的風險應對能力。
10. 與在地利害關係人合作發展農業技術：結合在地原住民農業系統/知識與現代生產技術的措施。
11. 理解土壤濕度的動態以改善灌溉：評估土壤濕度與養分監測工具的成本效益，及如何最有效推廣，以促進農民學習土壤濕度與養分的動態變化，改善其灌溉排程的決策。
12. 提升灌溉系統供水的彈性-1：開發具成本效益的方法與技術，以改善既有缺乏彈性的系統，並設計讓農民能最大化控管灌溉管理的新方案。
13. 提升灌溉系統供水的彈性-2：開發具成本效益的抽水與農業用水管理技術，使小農(個別與集體種植)，都能灌溉其農地。
14. 提升灌溉系統供水的彈性-3：建立管理結構，在提供農民安全取水的同時，確保取水維持在水資源永續使用的範圍內。

要使上述研究主題蓬勃發展的條件是全球性組織有以下四種典範轉移，包含：1)將重點放在能維持食物安全與促進小型農戶生計的系統、2)從單純提升產量的思維轉變為透過市場連結，生產高價值作物或創造附加價值、3)WTO 與 IMF 需要提出可以協助全球南方國家發展支持在地食物系統的政策、4)全球北方應協助全球南方國家擺脫依賴糧食進口和昂貴技術輸入的模式，轉為支持發展在地加值與具韌性的系統。

本文所提出之研究與發展建議乃由研究者之經驗出發，需留意文中提及的內容可能有以非洲情形過度一般化至全球其他區域的現象，然其觀點仍可供反思我國農業發展政策。我國之農業亦走過從關注產量到注重品質的過程，目前之農業乃在維持一定糧食自給率的前提下，以生產高附加價值作物、結合休閒農業、導入智慧農業為主要之發展趨勢。由於農業人口老化，

台灣農業永續發展之根本問題在增加青年從事農業之意願。近年來政府投入許多資源鼓勵青農返鄉，包含提供農業經營準備金、技術輔導、通路媒合等協助。然而，除了協助發展「個體戶」，農業發展需從「聚落」的整體性觀點思考農村出路，我國「地方創生」政策即為以此出發的農村永續發展策略。在研究的缺口上，目前以青農為對象的研究主要聚焦於創業與商業模式、電子商務與數位工具的應用、青年返鄉歷程等，將青農與農村聚落發展節合之研究較為缺乏，實為未來研究者可以投入的範疇。

在技術層面的建議上，本研究反覆提及技術的開發需考量其成本有效性，而我國自然工程學科較擅長技術應用或研發，對於成本效益分析的訓練往往是較為缺乏的，這也使許多技術從開發到落實於農民的實際應用，有一大段之落差。以近年興起的智慧農業為例，於田間安裝感測器，透過了解田間環境資訊與氣候資訊最佳化種植流程，為一具技術可行性之方案。然而，我國以小農種植為主要模式，此套生產管理流程需前期需投資硬設備且有操作維護之成本，對於個體農戶是否具有「成本效益」？未來關於智慧農業之研究包含智能感測、自動影像辨識、自動化機具、無人機應用等都需納入成本效益之分析，方能更務實的理解這些技術的應用性。

摘要翻譯及註解：王聖璋 助理教授

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**Research and development needs in agricultural water management to
achieve sustainable development goals**

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ABSTRACT

The United Nations calls for action to achieve 17 sustainable development goals (SDGs). We argue that the current development paradigm is an impediment to achieving several of these goals. We identify 14 agricultural research and development (R&D) needs, which ought to be addressed to achieve critical SDGs. We also identify the paradigm shifts required, particularly from global and international organizations, to facilitate this R&D and implement its outcomes. Importantly, the Global North² would have to divert its focus from securing access to cheap land, water and labour that is primarily used to generate agricultural exports and business opportunities for Global North investors. Instead, the focus needs to be on creating opportunities for local farming communities to produce food for domestic markets, increase income and generate local jobs and business opportunities. Circular food systems can support a range of SDG goals, such as no hunger and zero poverty and slow migration, especially of youth, to big cities or foreign lands with insecure jobs.

KEYWORDS

agricultural water management, food insecurity, Global South, research and development, sustainable development goals.

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綠色技術因應水資源短缺：

創業型企業可能帶動水資源管理實踐的轉型

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摘要

儘管現代企業實務對環境永續轉型有所貢獻，關於各類綠色技術及其應用方式的相關資訊仍相當有限。因此，辨識並分類聚焦於綠色技術管理實務的商業模式成為一項重要課題。雖然過去十年間關於綠色技術商業模式的文獻逐漸受到重視，然而跨領域對此日益成長現象的研究仍處於起步階段，且發展零散。本研究聚焦於全球水資源管理對綠色技術的需求，指出綠色技術之管理實務在該領域中仍屬研究空白，尚無前人深入探討。未來研究應進一步針對綠色創業企業的管理實務進行探討。現有文獻指出，透過綠色創業企業的管理策略以及全球綠色水處理技術的應用，有助於緩解水資源危機。作者認為，本研究對未來以綠色技術管理實務為基礎的政策制定研究將具高度參考價值，並能透過營造綠色企業環境，促進環境永續。

關鍵字：水資源短缺、綠色創業、社會企業、氣候調適、水即服務

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註解

本研究的核心問題設定於全球水資源短缺日益惡化的情境下，尋求如何以創新的綠色技術與商業模式回應此一挑戰。作者指出，傳統的公部門供水體系往往難以在資源有限、基礎設施老化或分布不均的地區提供穩定、安全且具有經濟可及性的飲用水，尤其在開發中國家的農村與偏鄉地區問題更為嚴重。面對這樣的結構性困境，研究提出一個具潛力的策略方向：發展具社會目標導向與市場運作能力的「綠色社會企業」，作為推動永續水管理的補充力量。

為具體說明此概念的可行性與成效，作者以印度社會企業「Water-as-a-Service (WaaS)」作為實證案例進行分析。WaaS 的設立宗旨即在於服務偏遠與水資源匱乏的社區，透過將太陽能發電技術與地下水過濾處理系統整合，提供小型化、在地化且具備財務可持續性的飲用水解決方案。其技術系統具備高模組性，便於快速複製與部署；此外，其管理架構並非採用傳統自上而下的模式，而是依賴在地社區參與與女性組織的主導，使得營運模式具有高度社會嵌入性與治理彈性。

WaaS 的成功關鍵，在於其技術創新與社會設計的雙重創新。技術面上，企業有效運用再生能源解決偏鄉缺電問題，並降低營運成本與碳足跡；組織面上，透過與社區建立信任機制、培育女性操作團隊與設置微收費制度，不僅創造就業，更深化當地居民對水資源治理的參與感與認同感。這樣的「水即服務」模式，突破了傳統政府或大型企業單向提供基礎服務的思維，重新界定了水資源作為公共品與市場商品的邊界，呈現一種結合永續發展與社會創新的新型治理模式。

針對這一成功案例，作者亦提出若干制度面建議。首先，政府可透過調整法規制度，例如簡化小型水務設施的審核程序、提供財政補貼或低利貸款，以及給予稅賦減免等誘因，促進類似模式的發展與擴散。其次，應在氣候適應與永續發展政策中，正式將社會企業納入國家治理架構，賦予其角色定位

與資源支援，使其能在與政府、企業及社區協作中發揮彈性、創新與回應在地需求的優勢。

本研究的發現對臺灣當前水資源治理轉型具重要啟示價值。隨著極端氣候事件頻率增加與區域用水不均加劇，臺灣在偏鄉地區的供水體系亟需兼顧彈性、永續與在地回應能力。特別是在水資源治理逐漸由中央集權走向多元治理的趨勢下，如何引入創新商業模式與社會企業力量，以補足傳統公部門供水體系之限制，成為當前政策與實務的重要課題。以下提出幾項對臺灣具體的政策建議：

1. 推動小型再生能源淨水示範計畫

借鏡 WaaS 模式，臺灣可在偏鄉、離島或水源不穩定地區推行太陽能驅動的模組化淨水系統。結合既有社區組織或農會資源，設立試點計畫，以建立低碳、在地、可複製的供水機制。

2. 鼓勵社會企業參與偏鄉水資源管理

將具永續目標的社會企業納入偏鄉供水政策網絡，透過技術輔導、創業補助與租稅優惠等方式，鼓勵青年投入水資源服務創業，補足公部門供應不足。

3. 設計具包容性的水費收費機制

參考 WaaS 以微型收費、預付制度進行營運，臺灣可發展具彈性的費率制度(如依用水量、用戶類型差異化)，同時保障弱勢群體的用水權益，提升費用回收率與制度公平性。

4. 整合永續與氣候調適政策，強化社區治理

政府在推動氣候調適政策時，可同步建構「社區導向」水資源治理架構，將在地居民納入決策、營運與監督機制中，培養水資源自治能力與使用者責任意識。

5. 導入智慧監測與管理技術

結合 IoT 感測(Internet of Things Sensing)、水質監測、遠端控制與雲端平台等技術，建立社區級智慧灌排與飲用水管理系統，提升運轉效率與即

時應變能力，符合臺灣朝向數位綠色轉型的政策目標。

6. 重構偏鄉水資源治理邏輯

不再以自來水普及為唯一目標，應轉向以「水即服務」為治理理念，針對不同區域設計在地化供水模式，強調小規模、模組化、使用者參與與社會嵌入性。

總體而言，本文所探討的綠色社會企業模式，展現了在資源受限與制度斷層地區中，透過技術創新與社區參與實現永續水管理的可行性。研究強調，唯有跨越傳統官辦與市場二元對立的治理思維，整合地方知識、社會力量與環境目標，方能因應當前全球水資源危機所帶來的多重挑戰。對臺灣而言，這不僅是一套具操作性的制度與技術整合方案，更提供了重構偏鄉水資源治理邏輯的契機，為實現氣候韌性、社會公平與綠色轉型奠定堅實基礎。

摘要翻譯及註解：許舒涵 助理教授

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**Green technology for water scarcity: An entrepreneurial business may
bring transformation in water management practices**

Muhammad Siddique, Manzoor A. Sanjrani, Keenjhar Rani

ABSTRACT

Despite the contributions of modern business practices to environmentally sustainable transformation, there is not enough information on different types of green technologies and their applications. Therefore, it is essential to identify and classify business models that focus on the management practices of green technology. While the literature on green technology business models has received increasing attention over the last decade, interdisciplinary research into this growing phenomenon is still in its infancy and fragmented. The study focuses on the need for green technology for water management worldwide. Such management practices for green technology represent a research gap in the study area because no one has worked in this field before. There should be research to address people's management practices of green entrepreneurial business. The literature highlights that the issue of water crises may be minimized with the management practices of green entrepreneurial business and by applying global green water treatment techniques. The authors believe that this study would be very beneficial for future research on policymaking based on management practices of green technology that promote environmental sustainability through a green business environment.

KEYWORDS

biological treatment, comprehensive business, environmental sustainability, green technologies, policymaking

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透過雪柏頓灌溉區三十年的土地與水資源管理夥伴合作計畫 實現永續灌溉

Carl Walters, Kelvin Bruce, Megan McFarlane

摘要

雪柏頓灌溉區 (Shepparton Irrigation Region, 簡稱 SIR) 位於澳洲維多利亞州北部, 面積達 50 萬公頃, 具有重要的環境與經濟意義。由於社區對鹽鹼化與地下水位上升日益憂慮, 該區於 1980 年代末期制定了 1990 至 2020 年的「雪柏頓灌溉區土地與水資源管理計畫」(SIRLWMP)。該計畫於 1990 年開始實施, 並獲得政府、農民及技術專家的支持。SIRLWMP 在當時的澳洲屬於獨特且創新的做法, 強調從長遠的角度看待環境永續發展。

由於環境問題往往無法在短期內顯現, 因此跨層級、長期且具調適性的夥伴關係變得至關重要。計畫中的所有合作夥伴學會了堅持與調整策略, 以培養社會經濟系統的韌性。該計畫協助該區成功應對並調適多項重大挑戰, 包括極端氣候事件、土地利用變遷及社區人口結構改變。這些挑戰都需要各方持續合作, 不斷優化 SIRLWMP 的方向與成果。

2020 年對計畫推行 30 年的成效所做的回顧, 顯示出在實現計畫目標方面已取得具體且深遠的成就。但工作仍未結束, SIRLWMP 將在更具挑戰的環境中持續推進。預期各方夥伴會持續合作, 並持續針對艱難的議題展開對話, 因為唯有這樣, 才能真正推動改變。

關鍵字：農業、生物多樣性、社區、排水、灌溉、自然資源管理、夥伴、鹽分、水管理

註解

本文回顧澳洲維多利亞州北部雪柏頓灌溉區過去 30 年的永續灌溉與土地、水資源管理歷程。該區因鹽鹼化與地下水位上升等問題，於 1990 年啟動「雪柏頓灌溉區土地與水資源管理計畫」(SIRLWMP)，結合社區、政府、農民與專家合作，推動長期環境永續發展的工作。計畫透過持續調適、夥伴網絡、社區參與與科學決策等，提升地區對氣候變遷、水資源匱乏與產業變動的適應能力。

該計畫促成了水資源管理、土地利用調整、生物多樣性保育及灌溉水資源效率的提升，如水利設施升級、農場用水效率改善及排水系統優化等。2020 年的評估指出計畫在水質、地下水位與環境用水等方面有顯著進展，但農業用水、原生植被及農村社區等方面則仍具有挑戰性。參與夥伴與社區普遍認為，這 30 年雖有不足與教訓，但整體對環境及社會皆有正向影響。未來該計畫仍須在氣候變遷、水資源壓力與社會變遷下持續更新與調整。

圖 1 概述了自 1990 年以來，SIRLWMP 在不同階段的重要發展與調適轉折，主要包含：

1. 1980 年代後期：社區警覺與計畫啟動

由於地下水位上升與鹽鹼化威脅，社區、政府及技術專家合作，開發 1990–2020 年 SIRLWMP，聚焦改善鹽分與水位問題。

2. 1990 年代中期：議題延伸與整合治理

從原先的鹽鹼化管理延伸到土壤養分管理、藍綠藻問題及生物多樣性納入灌溉與排水系統設計。並成立 Goulburn Broken 流域管理局(GBCMA)，促進水域管理與計畫整體協調。

3. 2000 年代：乾旱與水改革挑戰

千禧年乾旱導致水資源緊縮，加速了水資源使用效率的改善及灌溉系統的升級。引進水權與土地的分離(Unbundling)制度，促進水市場運作。

4. 2016 年：計畫更新與「韌性」思維

強化對社會—生態系統「韌性」的重視，界定了五大關鍵屬性，作為未來風險管理的核心指標。

5. 2020年：30年成果回顧與未來規劃

經評估後，確認 SIRLWMP 對水質、地下水位與環境用水改善有顯著成效，但農業用水、原生植被與農村社區等方面則仍面臨挑戰。預期未來將啟動計畫更新，以因應氣候變遷、水資源減少及農業系統轉型的需求。

The adapting Plan

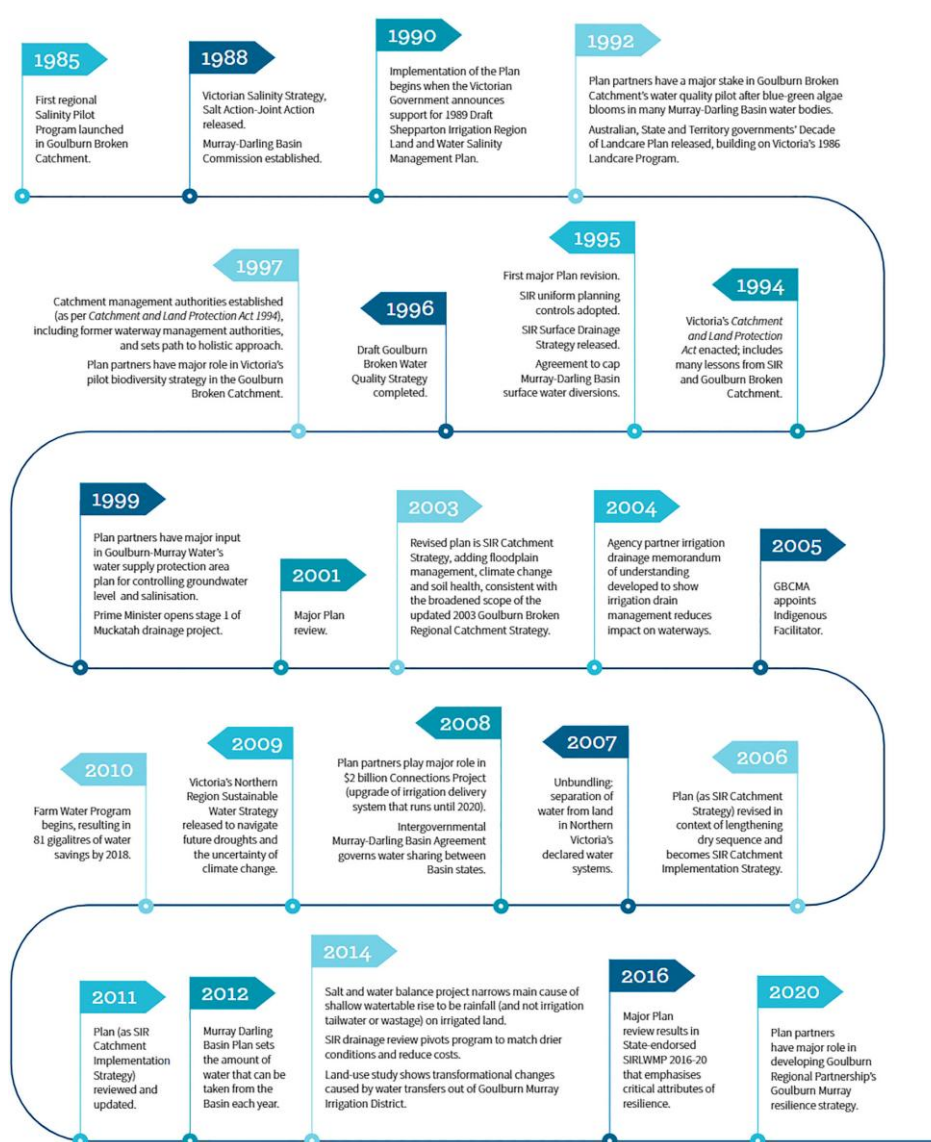


圖 1 SIRLWMP 主要里程碑與調適關鍵

該圖清楚呈現 SIRLWMP 計畫從單一的環境問題，逐步轉型為一個全方位、動態調適的土地與水資源管理機制，反映其因應自然與社會變遷的歷程。

圖 2 統計了 30 年間 SIR 土地與水資源管理計畫 (SIRLWMP) 實施的具體成果，包括：

1. 排水與地下水管理

建設了超過 760 公里的地面排水系統，有效減少淹水及鹽鹼化風險。設置了 4,500 多口淺層地下水井，控制地下水位並降低鹽分累積。

2. 農場規劃與用水效率

完成超過 5,600 份農場全區規劃，協助農民提升用水效率與整體土地管理。實施農場灌溉設施升級，改善灌溉效率並節省用水。

3. 生態與生物多樣性

透過規劃與工程改善了濕地與自然棲地，增進生態系統健康。在排水設計中融入原住民文化與自然景觀，如設置蜿蜒的排水道與蘆葦床，兼顧排水與生態。

4. 社區與政府投資

政府與社區共同投入了大量資金，藉此支持計畫執行與基礎設施建設。這些成果直接對應於提升水質、穩定地下水位、優化水資源分配，並為當地農業及社區發展建立了穩定的基礎。透過工程與管理措施，SIRLWMP 成功提升了該區域的永續灌溉與自然資源治理能力。



圖 2：1990–2020 年雪柏頓灌溉區（SIR）計畫的成果

圖 3 從五個關鍵屬性評估該地區的社會生態系統變化，並以評分形式呈現這些屬性的變化趨勢：

1. 水質

水質顯著改善，主要得益於營養鹽與鹽分管理、灌溉與排水系統的優化，以及農場整體規劃的推動。

2. 地下水位

地下水位穩定，過去因地下水位上升帶來的鹽鹼化風險已經被控制，但仍需要持續監測，主要受降雨與灌溉面積的影響。

3. 環境用水的滿足

環境用水的供應有所改善，但也帶來季節性流量對河岸生態的衝擊，如何找到環境與用水需求的平衡仍待進一步努力。

4. 農業用水的滿足

農業用水的滿足度降低，特別是在經歷千禧乾旱後，水資源緊縮迫使農業系統需持續調適，這是目前最具挑戰的議題之一。

5. 原生植被與農場及區域的可行性

原生植被覆蓋率不足 3%，雖有改善但仍不及需求，許多受威脅的生態系及物種仍面臨衰退風險。農村及農場也因水資源變遷與市場壓力而受威脅。

這些評估顯示，SIRLWMP 對於水質、地下水位及環境用水的永續管理成效顯著，但在農業水資源、原生植被保育與農村發展等方面，仍需要持續努力。

Critical attribute	Contribution to SIR system		Long-term risk of tipping	
	1990	2020	With current support	With no support
Water availability for the environment	POOR	OK	MEDIUM	HIGH
Water availability for agriculture	EXCELLENT	POOR	VERY HIGH	VERY HIGH
Water quality	VERY POOR	OK	MEDIUM	HIGH
Wattables	POOR	OK	MEDIUM	HIGH
Native vegetation extent	VERY POOR	VERY POOR	VERY HIGH	VERY HIGH
Farm and regional viability	GOOD	POOR	HIGH	VERY HIGH

圖 3 1990~2020 SIRLWMP 執行的長期影響評估

文中提出永續灌溉與水資源管理的成功絕非單靠技術或政策就能達成，而是仰賴「社區、政府、產業」等多方長期合作與信任的累積。雪柏頓灌溉區的案例，展現出地方社區在永續發展所扮演的潛力，以及透過動態調整與制度創新，應對環境、經濟與社會三重挑戰的智慧。該計畫中將生態、文化（如原住民文化）與農業結合進土地與水管理，不僅強化了生態韌性，也提升了社區認同。雖然仍有不足，如生物多樣性監測不足、對土地使用調整影響有限，但這也說明永續治理是一個「不斷學習與修正」的過程。

對台灣而言，特別是在面對水資源分配衝突、農業轉型及社區參與不足時，如何建立類似的長期夥伴機制、跨領域協作及社會溝通平台，將是我們邁向永續農業水管理的關鍵。

摘要翻譯及註解：張煜權 教授

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Thirty years of partnerships to achieve sustainable irrigation through Shepparton Irrigation Region Land and Water Management Plan

Carl Walters, Kelvin Bruce, Megan McFarlane

ABSTRACT

The Shepparton Irrigation Region (SIR) is an environmentally and economically significant area in northern Victoria of Australia covering 500,000 ha. The 1990–2020 Shepparton Irrigation Region Land and Water Management Plan (SIRLWMP) was developed in the late 1980s due to community alarm around increasing salinity and groundwater tables. The regional community (with the support of government, farmers and technical experts) started implementing the plan in 1990. The plan was unique and innovative in Australia in its approach to taking a long-term view of environmental sustainability. A long-term and adaptive partnership approach across all levels was vital because environmental problems did not always become apparent in the short term. All of the partners involved in the plan learned to persist and adapt their approach to build resilience in the socio-economic systems. The SIRLWMP has enabled many serious challenges to be successfully navigated and adapted to including extreme climate events, changing land use and community demographics. Each of these challenges required the ongoing collaboration of many partners to continuously improve the direction and achievements of the SIRLWMP. A 2020 review of the achievements of the 30 years of implementation showed the quantifiable breadth and depth of achievements against the plan's goals. However, there is still more work to do, and the SIRLWMP continues beyond 2020 in a challenging environment. It is expected that partners would continue to work together and continue to talk through difficult issues—because this is how real change happens.

KEYWORDS

agriculture, biodiversity, community, drainage, irrigation, natural resource management, partnerships, salinity, water management

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水資源安全世界之農業用水管理研究與創新

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摘要

現行糧食系統無法永續之意識提升，在氣候變遷下，農業水資源管理 (agricultural water management, AWM) 需要改革性的研究、開發與創新，以改造水及糧食系統。我們提供研究努力、挑戰、機會及創新之概述，以改善水資源管理及永續性，尤其在農業領域。我們強調，在水資源日益短缺與不安全下，永續農業水資源管理是平衡人口增長與糧食需求之核心，並影響環境與社會經濟成果。透過正在發展之創新技術，以永續灌溉技術、灌溉現代化與智慧水資源管理優化用水效率與生產力，然而，這些創新仍須充分解決與水資源取得、基礎設施及全球南方技術發展落後方面之公平性、不平等與社會正義問題。這需要採納如「水-能源-糧食」(water-energy-food, WEF) 關聯所提倡之跨學科方法，以更好地預測與平衡利弊，最佳化協同效益並降低調適不良的風險。透過這類跨學科方法，農業水資源管理之創新能更充分考量在地的社會經濟、治理、制度與技術限制，從而實現更具情境化及相關性且可擴展的創新。

關鍵字：永續發展、轉型、水資源安全、水-能源-糧食

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註解

資源永續是現今全球的共同目標，尤其水為生命必備條件資源，如何妥善運用水資源，是水資源管理關鍵議題。全球淡水資源本就有限，僅佔全球地表面積的 0.8%，其中超過 70% 被用於農業用途，但在氣候變遷下，全球暖化正影響降雨時空分佈及型態變化，水資源短缺與不安全情形加劇中，台灣地處熱帶與副熱帶區域交界處，氣候特徵多元且氣象水文交流複雜，氣候變遷與氣候多變性會對水文氣象相互作用產生影響，進一步影響水資源可取得性，且台灣雖降雨豐沛，但由於地形呈現山勢陡峭平原窄小，山高水短，水資源不易蓄存，因此，台灣身為農業型國家，大量農業用水使得水資源取得與利用之永續性在農業水資源管理領域至關重要。

本研究提出之農業水資源管理(AWM)研究方法，能更加全面瞭解農業用水背景及系統，並針對未來氣候變遷下農業用水管理方法創新與變革，灌溉是其中一項策略，以永續灌溉技術、灌溉現代化與智慧水資源管理改善水、土地與糧食循環永續性，在農業水資源管理中為最佳化發揮灌溉 AWM 策略，可先評估灌溉規模與技術轉型之潛在效益，如溝灌、噴灌和滴灌等，近年常用灌溉有效性指標-農業用水生產率(water productivity, WP) 衡量各系統層面之灌溉性能，以減少農業用水確保用水效率並維持或提高作物生產率為目的。除減少農業用水外，非常規水資源為可用於補充傳統供水的非傳統水源，包含雨水收集、工業廢水回收循環利用與海水淡化等，為灌溉、工業和其他非飲用水用途提供替代水源。此外，AWM 之關鍵研究與創新還包括灌溉計畫之治理、管理和控制，特別強調「誰做什麼、如何做」及其對灌溉農業成功之影響。

優先考慮雨養農業往往比灌溉更值得，摩洛哥的研究結果表明，投資雨養農業對國家經濟的利潤更高，農業發展應優先考慮雨養農業。除此之外，農業水管理與能源管理、節水節能以及降低成本密切相關，可能其他相關資源的不可持續消耗產生反彈效應，形成惡性循環，要進行更多研究加以評估，

例如以水、能源和食物 (WEF) 關聯，從水、能源、食物、環境與健康之角度，評估灌溉與人工補給廢水排水等非常規水資源對環境與健康之影響，處理非常規水過程比處理未經處理之淡水能耗更高，在農田、渠道及雨水體中之聯合發電再生能源，例如微型水力發電，可優化能源利用效率。對於台灣而言，因氣候條件，雨水收集與雨養農業可能具相當優勢，在外島地區，如澎湖，則有海水淡化廠，而海水淡化廠之建立除考量經濟及能源因素外，亦須考量當地生態環境(珊瑚礁等)，在氣候條件、灌溉排水系統與河川地形條件下，則可評估微型水力發電可行性。

第四次工業革命 (4IR) 下，農業生產系統中之物聯網、虛擬實境、遙感、3D 列印、大數據與人工智慧技術逐漸普及，例如：虛擬實境技術可用於模擬灌溉系統管道中流體之流動情形，進行摩擦分析，進而研究改善輸水與施水效率之方法。將 4IR 技術用於整合 GIS、遙感等資訊，可更加全面地大規模檢視農業系統成效，若與情境規劃模擬應用，可提前進行灌溉關聯規劃。

台灣之渠道除傳統灌溉功能外，亦結合排水功能，形成灌溉排水系統，部分渠道在都市化中轉型，結合休閒遊憩元素，無論在農業地區或都市地區，皆可以農業水資源管理的研究與創新進行規劃設計，在氣候變遷與經濟發展下以灌溉排水系統為基石，進行多元關聯研究與評估水資源管理，於農提升作物生產率；於能源結合發電設備等，產生多方效益。

摘要翻譯及註解：林遠見 教授

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**Research and innovation in agricultural water management
for a water-secure world**

Mark D. Smith, Alok Sikka, Tinashe L. Dirwai, Tafadzwanashe Mabhaudhi

ABSTRACT

There is increased awareness that the current food system is unsustainable and that transformative research, development and innovation in agricultural water management (AWM) are needed to transform water and food systems under climate change. We provide an overview of research efforts, challenges, opportunities and innovations to improve water resource management and sustainability, especially in the agricultural sector. We highlight how sustainable AWM is central to balancing the needs of a growing population and increasing food demand under increasing water insecurity and scarcity, with environmental and socio-economic outcomes. Innovative technologies are being developed to optimize water use and productivity through sustainable irrigation technologies, irrigation modernization and smart water management. However, these innovations still need to fully address equity, inequality and social justice concerning access to water, infrastructure and the delayed technological advances in the global South. This requires adopting transdisciplinary approaches, as espoused by the water–energy–food (WEF) nexus, to better anticipate and balance trade-offs, optimize synergies and mitigate risks of maladaptation. Through such transdisciplinary approaches, AWM innovations could better consider local socio-economic, governance, institutional and technological constraints, thus allowing for more contextualized and relevant innovations that can be scaled.

KEYWORDS

sustainable development, transformation, water security, WEF nexus

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亞洲農場層級提升水生產力之實務作法綜述

R. P. Meena, V. Karnam, H.T. Sujatha, S.C. Tripathi, G. Singh

摘要

全球人口已於 2022 年達 8 億，預計至 2037 年增至 9 億。人口成長造成食物與衣物的需求上升，進而加劇對有限水資源的依賴。然而，農業可用淡水量正隨著過度開發與氣候變遷而持續下降。都市化加劇城市擴張，使水資源競爭更加激烈。因此，農業水資源分配需重新檢討，並尋找提升灌溉效率與水生產力的策略。

本研究彙整了 2000–2023 年亞洲農業水生產力 (Water Productivity, WP) 相關文獻，內容涵蓋：WP 定義與評估方式、導致亞洲農業 WP 偏低的成因，以及可行的提升策略。這些策略包括：農藝技術（如：精準整地、種子滲調、保護性耕作）、遺傳改良（選育高 WP 品種）與智慧灌溉技術（IoT、自動排程）。本綜述提供決策者與農民可實行的灌溉與管理工具，有助於提升農場層級的水資源利用效率。

關鍵字：微灌溉 (Microirrigation)、灌溉排程 (Irrigation scheduling)、保育型農業 (Conservation agriculture)、水資源短缺 (Water scarcity)

註解

隨著全球人口持續成長與都市化快速擴張，糧食與用水需求同步上升，尤其在農業用水佔據總淡水資源消耗七成以上的背景下，農業用水的永續利用成為全球關注的核心議題。根據聯合國糧農組織（FAO）統計，全球糧食生產需仰賴穩定且高效率的灌溉系統支撐，然而亞洲地區長期面臨傳統灌溉技術落後、地下水過度抽取、水資源分配制度不完善等結構性問題，加劇了農業用水浪費與水資源競爭。為因應氣候變遷導致之降雨不確定性與水源不均，農業系統亟需發展以提升單位用水生產效益為核心的管理策略，即提升「水生產力」（Water Productivity, WP），使有限水資源達成最大化糧食生產與經濟效益的目標。

在此背景下，Meena 等人於 2023 年發表於 *Irrigation and Drainage* 期刊之文章(Practical approaches to enhance water productivity at the farm level in Asia: A review)，系統性彙整 2000 至 2023 年間亞洲地區農場層級提升 WP 的可行技術與管理策略，嘗試從農藝、生理、灌溉、遺傳與智慧決策等多面向，建構出一套適用於氣候與資源條件多樣化的農業用水提升框架。該研究採用文獻回顧方法，從 Scopus、PubMed 與 Google Scholar 等國際資料庫中篩選出具代表性與實務價值之研究成果，總結出提升農業 WP 的三大主軸：農藝與管理技術、灌溉與排程策略，以及作物選育與 G×E×M（基因×環境×管理）整合架構。研究特別關注於農場層級的可操作性與在地適應性，並試圖從定量指標中歸納出高效率技術的預期效益。

研究發現顯示，亞洲地區農業 WP 偏低的主要原因包括：灌溉系統設計不良與低效率、過度依賴地面灌溉（如淹水灌溉）、農民對節水技術的認知與採用率低、政策補貼機制造成地下水過度抽取，以及農田水利設施老舊與維護不足。其中，傳統地表灌溉效率僅為 25%至 40%，大量灌溉水未被有效利用即流失於滲漏、蒸發與逕流過程。研究整理顯示，精準整地技術能有效改善灌溉均勻性，節水率可達 13–40%；使用生物可分解塑膠覆蓋物可

減少土壤蒸發、保溫與抑草，同時提升作物初期生長與灌溉效率；作物替代與多樣化，如在水資源短缺地區改種旱作作物（如玉米、小麥、高粱）取代高需水作物（如水稻與甘蔗），可提升整體輪作系統之水分利用效率達 20–40%。

在灌溉技術層面，研究指出滴灌與微灌為提升 WP 最具潛力之技術，能節水 25–70%，並提升作物產量 20–50%。而調缺灌溉（Regulated Deficit Irrigation, RDI）則是在作物非關鍵生育期故意減少灌溉，達成節水 5–50% 且不顯著降低產量的效果。此外，地下滴灌系統、滴頭感測裝置與自動化控制系統（如物聯網灌溉平台）可結合土壤水分感測器與作物模型，實現「以需灌溉」，避免傳統灌溉過量問題，提高精準度與反應性。研究亦彙整灌溉排程與決策支持工具，如 CROPWAT、AquaCrop、IrriSat 等模型，可用於不同作物與土壤類型下之灌溉時機與灌溉量預估，為農戶提供實用的操作建議。

此外，文章強調作物品種選育與遺傳潛能開發的重要性。透過 G×E×M 整合策略，能針對特定氣候與水分條件，選育高水分利用效率的作物基因型，並搭配合理栽培管理措施，有效提升作物在乾旱與水分限制條件下之生產穩定性，例如抗旱性強、根系發展快速、對水分利用效率高的品種在水資源受限地區具有高度推廣潛力。

在綜合討論中，作者指出，雖然多數技術已證實具備節水與增產效果，但實際推廣仍受限於初期投資成本高、技術門檻、維護困難與農民接受度等因素。因此，建議各國應透過政策補貼、灌溉貸款、教育訓練與示範田推動，加強技術在地化與規模化應用。同時，制度層面應檢討現行地下水抽取與電費補貼機制，避免資源浪費與政策誘因失衡。作者也強調，單一技術難以解決複合型水資源問題，應以系統思維整合多元策略，結合物聯網、水資源模擬、作物模型與在地農民參與，打造多功能水資源管理平台，方可真正實現農業用水效率的根本改善。

對臺灣而言，本研究提供重要政策與實務啟示。臺灣地狹人稠，農業用

水競爭激烈，特別是中南部地區常見於春作期間出現乾旱與灌溉水不足問題。若能仿效文中所述技術，如導入精準整地與滴灌技術、推廣旱作替代方案（如水稻轉作玉米）、建立灌溉排程模型與感測平台，以及進行 WP 長期監測與評估，將有助於提升全國農業用水效率與糧食韌性。同時，台灣亦可考慮將 WP 納入相關灌溉管理單位之管理指標，建立本地化之水生產力評估制度，以科學化、系統化手段推動農業節水與永續發展之雙重目標。

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Practical approaches to enhance water productivity at the farm level in

Asia: A review

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ABSTRACT

The global population is constantly increasing, reached 8 billion in November 2022 and is expected to reach 9 billion by 2037. This increased population is expected to increase the demand for food, clothing and shelter, which in turn are heavily dependent on limited water resources. The available freshwater resources for agricultural use are further declining due to overexploitation and changing climate in the major food baskets of the world. This increasing water scarcity is exacerbated by expanding cities due to increasing urbanization. This calls for a new look at the allocation of water to agriculture. Therefore, the development of new strategies to improve agricultural water use may serve as an important adaptation strategy. This review attempts to include a comprehensive review of the literature on (i) the status and definition of water productivity and (ii) factors responsible for low water productivity (WP) in Asian agriculture. Furthermore, it contains practical approaches to enhance water use efficiency at the farm level covering all field crops and a range of soil types, which include (i) agronomic interventions; (ii) genetic interventions, such as the identification and cultivation of crop cultivars with high WP; and (iii) genotype, environment and crop management interactions for higher WP.

KEYWORDS

microirrigation, irrigation scheduling, conservation agriculture, water scarcity

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從量測效能及在中國智慧發展的角度檢視測滲計

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摘要

測滲計(lysimeters)是研究水文循環中入滲、地表逕流和蒸散過程的關鍵儀器，並在促進高效節水灌溉方面扮演著關鍵角色。本文對測滲計的發展過程和研究狀況進行系統化的回顧，從簡單設計到複雜設計，從單台儀器到群集儀器，從人工量測到智慧監測。首先，根據近 20 年來中國測滲計專利的情況，介紹了各類測滲計的工作原理。其次，本文分析了不同測滲計的量測性能和應用範圍，並進一步探討各種稱重測滲計的稱重穩定性。第三，透過分析測量誤差的來源，從環境控制和感測器補償兩方面分析提升測滲計可靠度的方法。第四，本文回顧測滲計自動化及訊息化的典型研究，並討論測滲計在複雜環境下未來智慧化發展及應用前景。最後，本文根據實驗資料集分析不同類型測滲計的量測效能，並針對開發高效能、高效率、高可靠度的測滲計提出一些建議，希望能促進智慧農業的發展。

關鍵字：智慧農業、測滲計、量測效能、可靠性改善、節水灌溉

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註解

測滲計是用來直接量測農業土壤水分平衡的儀器，可以研究水文循環中的滲透、地表逕流、地下逕流及蒸發散等過程，在推動高效節水灌溉、智慧農業方面扮演舉足輕重的角色。本文根據中國近 20 年來測滲計系統的相關專利及論文，全面檢視測滲計技術的研究進展，並分析測滲計的工作原理、性能及智慧化發展的可能性。

依工作原理區分，測滲計分為非稱重式及稱重式兩大類，非稱重式測滲計主要包括重力流式(Gravity Flow lysimeter)及地下水式(Groundwater lysimeter)。稱重式測滲計包括懸吊式(Suspended lysimeter)、可稱重的重力式(Weighable Gravitation lysimeter)及槓桿式(Lever lysimeter)。非稱重測滲計係透過控制地下水水位及量測補給水量及滲漏水量來估計蒸散量。稱重測滲計則是依據水平衡公式，透過實驗土壤箱的質量變化量測土壤中水分變化，從而確定作物的蒸散量，因此會受氣候及外在環境影響，例如夜間露水、日間蒸發散等。

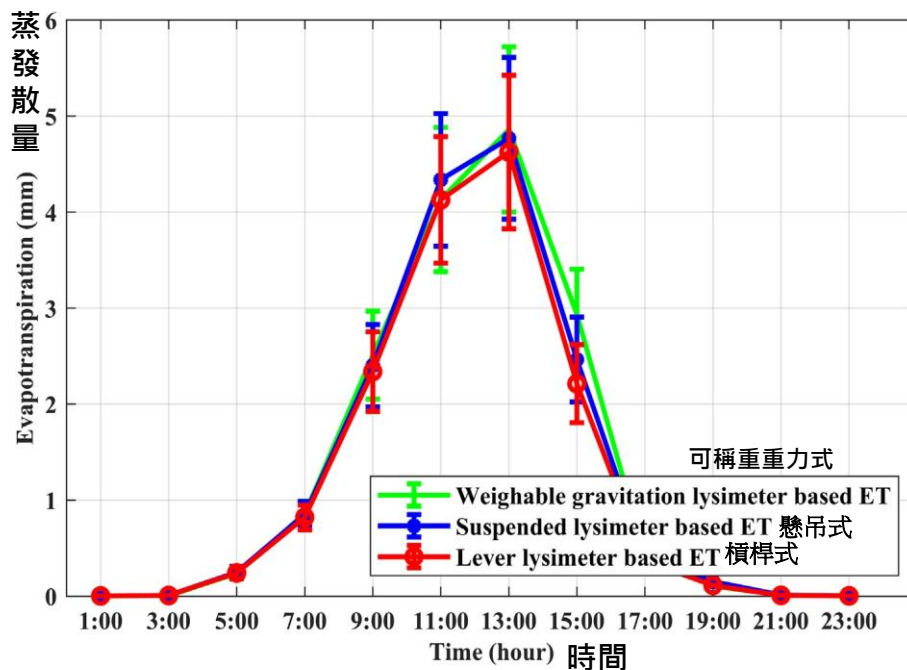
測滲計的量測準確度受到不同工作原理及環境因素的影響，導致不同的測滲計具有不同的應用範圍、量測解析度及量測誤差。非稱重式測滲計透過測量深層滲漏和補給水量來計算蒸散量。溫度對植物根系生長和土壤水分吸收起著關鍵作用。不同的溫度會嚴重影響植物和微生物的生長，進而影響實驗土壤箱的棲息環境，最終影響蒸散量。溫度漂移是影響感測器測量精確度的常見因素，會導致測量誤差，因此必須透過補償修正感測值減少誤差。

影響測滲計測量性能的主要環境因素是風和溫度。在現場實驗中，風的干擾是不可避免的，會造成土壤箱震動，影響稱重。經測試不同類型測滲計之量測效能如表 1。

表 1 各類型測滲計量測效能一覽表

類型	範圍	解析度	最大容許誤差	重現誤差
重力流測滲計	/	0.1 mm	±0.5 mm	≤0.2 mm
地下水式測滲計	/	0.05 mm	±0.2 mm	≤0.1 mm
懸吊式測滲計	0–40 t	0.02 mm	±0.1 mm	≤0.05 mm
可稱重重力式測滲計	0–1 t	0.05 mm	±0.2 mm	≤0.05 mm
槓桿式測滲計	0–50 t	0.01 mm	±0.05 mm	≤0.015 mm

一般而言，非稱重式測滲計的特點是結構簡單、成本低、操作方便、測量精度低。相較於非稱重式測滲計，大多數稱重式測滲計的測量精度高、結構複雜且成本高。但稱重式測滲計之量測精度及穩定性均優於非稱重式測滲計，因此，許多田間實驗站以稱重滲透儀為主要監測儀器，非稱重滲透儀為輔助監測儀器，共同研究作物蒸發散量。針對稱重式測滲計，本文在田間實驗站放置了懸吊式測滲計、稱重式重力測滲計和槓桿式測滲計等三種類型，比較其量測效能，由結果顯示三種測滲計量測作物蒸散量結果相近，濕度測量的結果也相近，如下圖所示。



總結本文相關建議如下，

一、在量測解析度與精準度提升方面，非稱重式測滲計的解析度可達到 0.1

mm 的要求，而稱重式測滲計的解析度則可達到 0.05 mm 以下，高精度槓桿式測滲計儀器更可達到低到 0.01 mm 的稱重精準度。在稱重測滲計中，槓桿式測滲計的稱重穩定性優於懸浮式與直接稱重式測滲計。儘管從環境控制和感測器溫度補償來提高量測的可靠性，但在高鹽分土壤和極寒地區的長期精度仍有待改進。主要受風、鹽度、溫度等外在環境及量測材料變形、劣化等因素影響。

二、在智慧型研究中，目前的測滲計用各種感測器來監控土壤和作物的濕度、鹽分含量、溫度及其他指標。這些指標可透過無線傳輸網路進行遠端監控。然而，近年來在中國農業水利方面新興的機器視覺與遙測技術並未與測滲計有效結合，因此仍需持續研究發展。

三、對於測滲計在複雜環境中的應用，目前測滲計的功能結構設計是為了增強其在具有挑戰性條件下的適用性，例如涉及冷熱交替溫度及凍土的條件。但是，還沒有標準化或普遍適用的測滲計結構，可適用於各種複雜環境。因此，未來的工作應著重於探索高精確度與可靠度的感測器，以建構更精確的測滲計系統。其次，未來的工作應該結合農業影像資訊與感測器監測資料，全面監測土壤水分、作物生長與生理指標，以提高農業灌溉的用水效率。同時著眼於整合區域氣候與土壤質地研究，以開發具有區域適應性的測滲計。

摘要翻譯及註解：丁崇峯 研究員

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**A review of lysimeters from the perspective of measurement performance
and intelligent development in China**

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ABSTRACT

Lysimeters are critical instruments for studying infiltration, runoff and evapotranspiration processes in the hydrological cycle and play a critical role in promoting efficient water-saving irrigation. This paper provides a systematic review of the development process and research status of lysimeters, progressing from simple to complex designs, from single instruments to clusters, and from manual measurement to intelligent monitoring. The working principles of various types of lysimeter were first described based on Chinese lysimeter patents over the past 20 years. Second, this paper analyses the measurement performance and application scope of different lysimeters and further studies the weighting stability of various weighing lysimeters. Third, by analysing sources of measurement error, the reliability improvement methods of lysimeters are analysed from the aspects of environment control and sensor compensation. Fourth, this paper reviews typical research on the automation and informatization of lysimeters and discusses future intelligent developments and application prospects for lysimeters in complex environments. Finally, the measurement performance of different lysimeters is analysed based on experimental data sets. This paper puts forward some suggestions for developing lysimeters with high performance, high efficiency and high reliability, hoping to promote the development of intelligent agriculture.

KEYWORDS

intelligent agriculture, lysimeter, measurement performance, reliability improvement, water-saving irrigation

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將灌溉系統轉變為智慧灌溉系統：土耳其案例研究

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摘要

土耳其國家水利工程總局 (DSI) 於 2022 年藉由推動 Imamoglu 農業灌溉自動化計畫，整合管路灌溉系統及自動化智慧灌溉技術，建立中央集中管理的資訊系統，透過監測數據建立作物-水量-產量等關鍵變量關係，以尋求最佳化灌溉水量，改善農業灌溉用水的管理與有效分配。本計畫之核心關鍵為基於地理資訊系統 (GIS) 的介面與介接整合即時數據，並建置電子化用水管理系統 (ESYS) 促進農民及用水利害關係人之積極參與。計畫中透過利用深度學習方法進行即時數據分析，以提供灌溉用水所需的即時資訊，進而達成顯著之節水成效並可兼顧產量的提升。Imamoglu 計畫專注於現代化智慧灌溉系統之落實，並已逐步成功推動 2,240 位農民之積極參與。藉由 ESYS 系統整合供灌決策所需資訊進而達到強化供水安全、遠端灌溉控制、土壤濕度監測、基於天氣資訊的灌溉計畫與集中管理的灌溉作物模式等各項優勢。本計畫目標在於促進用水效率之提高、糧食產量的大幅提升，並可作為未來現代化之灌溉系統的成功學習典範。本計畫主要亮點績效包括節水量達到 65%–70%，減少能源及節省燃料高達 90%，並減少高達 90% 的勞動力，進而達成節省人力成本與提高灌溉管理效率之具體成果貢獻。

關鍵字：人工智慧、灌溉管理、智慧灌溉、用水管理。

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註解

近年來因氣候變遷造成水資源不穩定之風險持續升高，保障用水供應安全已成為全球糧食安全之首要挑戰。同時為了提高農業增產，必須透過現代化灌溉技術的改進與用水效率之提升，以確保水資源的永續利用。為解決此迫切的課題，必須重新規劃現代化的灌溉系統導入先進的深度學習技術打造建置成智慧灌溉系統，利用創新系統進行數據分析以優化灌溉用水量，不僅減少水資源浪費又能提高作物產量。

本文為土耳其國家水利工程總局（General Directorate of State Hydraulic Works, DSI）Mehmet Akif Balta 等人所提出目前土耳其所實施之現代化灌溉基礎設施計畫，包含投資建設嶄新之加壓管路灌溉系統，以及透過感測器及物聯網(IoT)相關設備提供土壤濕度、溫度及降水等即時監測數據，並導入人工智慧(AI)之機器學習數據分析技術與驅動精確的灌溉策略之決策過程，以徹底改變水資源管理之效率與用水精度提升。綜整本文所獲致之重要結論歸納如下：

1. 土耳其國家水利工程總局（DSI）規劃建置中央集中式現代化灌溉水資源管理系統，核心系統為電子水管理系統（Electronic Water Management System, ESYS），主要架構及內容包含：
 - (1)基於 GIS 介面的監測資料、水利系統圖資及用水模擬數據；
 - (2)線上即時之氣象、作物、土壤及水資源整合監測站數據；
 - (3)線上控制與決策命令下達之整合自動化灌溉用水系統；
 - (4)中央集中管理之農業灌溉自動化整合智慧管理系統。
2. DSI 建設管路灌溉及管網優化之方式實現水資源有效利用並達成顯著之節水成效，包括跨田區之灌溉管路佈設、管路材料的選擇、灌溉面積、控制管路水量之水閘門、空氣閘及截水閘門等機械設備之定位安裝。此外，為了進行管路優化透過開發專業軟體，分析灌溉區域之最短、最適管網設計，以確保各種管路類型及材料（包含玻

璃增強纖維、鋼或高密度聚乙烯)之不同管路直徑及長度均能符合壓力承受之標準。此外，具智慧化之自動閘門系統及預付費智慧電錶均已納入至整個智慧管網系統之興建設備元件中。

3. 目前正進行之 Imamoglu 自動化灌溉工程計畫是土耳其最大的管路灌溉計畫，覆蓋面積為 2,623 公頃均配備先進的自動灌溉設施，包含 280 座 H 型雙出口自主給水栓(SIV)、55 個壓力感測器、15 個流量計、30 個濕度感測器、5 個氣象站，共計有 2,240 位農民及相關現場設備操作人員參與使用 ESYS 為基礎之農業灌溉自動化系統。
4. 本計畫之使用者可藉由各項灌溉監控資訊的數據分析及利用遠端中央控制設備，進行遠端啟動或停止水流，增加系統多功能性以強化用戶對系統使用需求的依賴。其中，重要組成元件包含如給水栓，是整個灌溉系統中將水分配到田地的主要設施；另外，包含四個主要的感測器，分別為壓力感測器用於監測管路水壓，超音波流量計應用於精確監控流速及水量，土壤濕度感測器透過持續監測土壤中的濕度，確定植物根部深度的水位並調整相應的灌溉量，氣象降水預報雷達系統用於監測及預報天氣狀況。利用人工智慧技術整合土壤濕度與氣象資訊，可確實達到降雨或田間土壤水分已足夠的情況下，系統將自動暫停灌溉，以減少不必要的灌溉用水浪費。
5. 本計畫授權之應用程式可分別在 Apple IOS 和 Android Play 上使用，每個自主給水栓 SIV 都保留有四個獨立的可訂閱用戶供使用，農民可以在獲得授權管理自己耕作的坵塊下，使用 SIV 用水或輪灌順序，包含灌溉開始至結束日期時間、申報灌溉用水操作、查詢取得觀測站數據並設定各種預警值等。

近年台灣亦受氣候變遷與極端氣候加劇影響，乾旱頻仍發生下各區水資源風險升高，在安全存糧無虞之前提下，國內陸續推動相關農糧及節水獎勵政策，希冀透過水資源供需調整稻作產業結構以提高國產雜糧生產。本研究推展之 Imamoglu 灌溉計畫已改變傳統農業水資源管理方式，為現代農業管

理發展邁出了重要一步。不僅可預先掌握可用水量的地點、時間及數量等即時資訊，更能有效的進行灌溉管理之配水規劃與提供安全無虞之穩定水量，建議可作為國內政府機關在從事灌溉技術改進及制定各區水資源與糧食政策之參考應用。

摘要翻譯及註解：王鵬瑞 博士

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Transforming an irrigation system to a smart irrigation system:

A case study from Türkiye (Turkey)

Mehmet Akif Balta, Muhammed Imran Kulat

ABSTRACT

The Imamoglu Agricultural Irrigation Automation Project aims to revolutionize water management and allocation in agricultural irrigation through the establishment of a central management-based system. By integrating modern irrigation technologies and systems, the project seeks to optimize water usage by monitoring key variables such as irrigation methods and plant–water–yield relationships. The electronic water management system (ESYS), at the core of this initiative, employs a geographic information system (GIS)-based interface and real-time data to facilitate active participation of farmers and water stakeholders. Through the utilization of deep learning technology and real-time data analysis, the system enables timely and informed irrigation planning, resulting in significant water savings and increased productivity. The project's implementation, focused on the Imamoglu Irrigation System, has gradually introduced a remote central management-based agricultural irrigation automation system to 2,240 farmers. Integrated with the ESYS, this system offers benefits including enhanced water supply security, remote access to irrigation control, soil moisture monitoring, weather-based irrigation planning and centralized plant pattern management. The project aims to promote efficient water usage, maximize food production and serve as a model for future irrigation projects. Key highlights include up to 65%–70% increase in water savings, up to 90% reduction in energy and fuel savings, up to 90% reduction in labour and personnel savings and more efficient irrigation management, among others.

KEYWORDS

artificial intelligence, irrigation management, smart irrigation, water management

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利用高解析度影像與 Google Earth Engine 估算 可耕地損失與灌溉需求

Majid Farooq, Fayma Mushtaq, Ubaid Yousuf

摘要

水資源的規劃與管理在如印度河流域這樣複雜的流域中至關重要，該流域由印度與巴基斯坦依據印度河水條約（Indus Water Treaty, IWT）共同管理，關係到糧食安全、環境保育、永續經濟發展及生計維持。本研究評估了過去 54 年間，Padshahi 與 Sindh Extension (SE) 兩條灌溉渠道集水區的可耕地損失情況，並運用高解析度衛星影像與 Google Earth Engine 的標準化植生指數 (NDVI) 推估結果，作為提升灌溉效率、減少水資源損耗及在 IWT 架構下永續利用有限水資源的策略依據。研究結果顯示，1966 年至 2020 年間，兩條渠道的灌溉農地面積已由 5127 公頃減少至 3501 公頃。其中 Padshahi 渠道的農地損失最為嚴重（1278 公頃），主要原因是農地/作物地大量轉變為建築用地（減少 69%）。相較之下，SE 渠道的變化較少（僅 348 公頃轉變為建築用地），轉變趨勢偏向園藝與種植型態。NDVI 的月變化也清楚顯示，隨著水稻播種季於五月展開，Padshahi（1900 公頃）與 SE（2600 公頃）兩渠道的農地皆出現高度灌溉需求。

關鍵字：agriculture、CORONA、GEE、印度河水協定、灌溉、NDVI

註解

本研究探討印巴共享的印度河流域 (Indus Basin) 中，查謨與克什米爾聯邦直轄區 (Jammu & Kashmir) 兩大灌溉渠道—Padshahi 與 Sindh Extension (SE) —流域在 1966 至 2020 年間的耕地變化與灌溉需求。該地區水資源分配受限於 1960 年印巴「印度水條約」 (Indus Water Treaty, IWT)，因此合理規劃灌溉資源對於糧食安全與永續發展極為重要。

研究以高解析度歷史 CORONA 衛星影像 (1966 年) 與現代 GeoEye-1 衛星影像 (2020 年) 為基礎，搭配 Google Earth Engine (GEE) 雲端平台與歸一化植生指數 (NDVI) 進行土地利用變化 (LULC) 分析與灌溉需求評估。研究方法包括：1) 不同年份影像的視覺數位化分類；2) 土地變遷矩陣分析；3) 利用 NDVI 分析灌溉面積的季節變化。

結果顯示，過去 54 年間兩個渠道的可灌溉農地總面積由 5127 公頃減至 3501 公頃。Padshahi 渠道的農地流失尤為嚴重，灌溉土地損失達 1278 公頃 (減少 51%)，而 SE 渠道損失為 348 公頃 (減少 13%)。最大宗的土地轉變是農耕地轉為都市建築用地，其中 Padshahi 的建成區從 5% 擴張至 51%，土地轉變達 834%，顯示快速都市化造成農地大規模流失。SE 渠道的主要變化則是農地轉作園藝果樹種植，反映出農業結構從高耗水稻作轉向較具經濟效益且耗水較低的作物。

此外，藉由 2021 年的 Sentinel-2 NDVI 時序資料，本研究亦估算灌溉需求的季節變化。Padshahi 與 SE 渠道於每年五月達到灌溉高峰，對應稻作播種期，需灌溉面積分別為 1900 與 2600 公頃。灌溉需求隨作物生長週期呈明顯月變化，冬季 (如一月) 需求最低，春末與夏季為高峰。研究進一步指出，NDVI 可有效鑑別灌溉與非灌溉區域，並有助於觀察因建成區混合綠化區 (如公園、街道樹) 所導致的影像誤判問題。

從政策層面而言，研究建議應將高解析度遙測與 GEE 分析技術納入 IWT 下的水資源分配機制，以補足現有統計與表格式資料的不足。研究亦

指出，土地利用轉變對於地下水補注、生態系統、糧食生產與氣候調節具潛在負面影響，因此強調土地規劃與水資源管理整合的重要性。尤其在都市擴張、人口成長與青年農業人口外移的背景下，如何保留有效農地與調整灌溉結構，是未來政策制定的關鍵。

結論指出，衛星影像與 GEE 平台提供可靠方法來追蹤耕地變遷與水資源使用，有助於建構精準的水資源管理策略，並建議未來擴大應用至整個印度河流域範圍。此外，應補強灌溉供水與非正式用水協議等資料來源，以提高土地與水資源評估之精確性。

摘要翻譯及註解：胡明哲 教授

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**Estimation of loss in arable land and irrigation requirements
using high-resolution imagery and Google Earth Engine**

Majid Farooq, Fayma Mushtaq, Ubaid Yousuf

ABSTRACT

Water resources planning and management are critical in intricate basins such as the Indus Basin, shared by India and Pakistan under the Indus Water Treaty (IWT) for food security, conserving the environment, sustainable economic development and supporting livelihoods. The present study assesses arable land loss within the Padshahi and Sindh Extension (SE) canal catchments over 54 years, utilizing high-resolution satellite imagery and Google Earth Engine's normalized difference vegetation index (NDVI) derivations for strategizing irrigation efficiency, minimizing water loss and ensuring sustainable utilization of limited water resources under the IWT. Results revealed that irrigated land has decreased from 5127 ha (1966) to 3501 ha (2020) in both canals. The Padshahi canal sees substantial loss (1278 ha), primarily due to the highest transitions from agricultural land/crop land (-69%) to built-up areas. The SE canal, experiencing shifts to horticulture and plantation, records relatively fewer changes in built-up areas (348 ha). The monthly variation in the NDVI clearly depicted the high demand for irrigation to cater to agricultural lands with the onset of the sowing season for paddy in the Padshahi (1900 ha) and SE (2600 ha) canals in May.

KEYWORDS

agriculture, CORONA, GEE, Indus Water Treaty, irrigation, NDVI

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黃河上游區域地下管線排水系統對作物水分生產率的影響模擬

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摘要

地下管線排水 (SPD) 可以為乾旱和半乾旱農業地區的農作物生產提供適宜的環境；但對屬於區域尺度的河套灌區 (HID)，使用 SPD 設計佈局則鮮少有人關注。本研究使用 HID 中的分佈式 SWAP-WOFOST (土壤-水-大氣-植物和世界糧食研究) 模型來確定最終地下管路的適當佈局。隨後，評估了適當的 SPD 對作物產量和水分生產率 (WP) 的影響。最後，調整作物分區，進一步提高作物水資源生產率 (WP)，並根據建議的 SPD 初步估算相應的新增耕地面積。結果顯示依建議的 SPD 分區後，春小麥、春玉米、向日葵的年平均產量與傳統佈局相比，分別提高 19%、7% 和 11%；水稻產量分別提高 13%、5% 和 10%。預計透過 HID 將傳統末溝更換為地下管線，可新增耕地面積約 3,489 公頃。因此，本研究所建議的地下排水管線設計和種植模式調整可以改善作物生長，並增加 HID 的耕地面積。

關鍵字：作物分區、分散式 SWAP-WOFOST 模型、地下水深、地下管路排水、水資源生產率

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註解

臺灣雖位處亞熱帶，年降雨量高達 2,500mm 以上，但其中近八成集中在汛期，乾旱時期（尤其春季）則常見農田缺水現象。近年如南部的曾文、烏山頭水庫水位屢創新低，導致一期稻作停灌的情況屢見不鮮。因此，如何提升農業水資源使用效率與耕地利用率，成為迫切課題。

隨著全球氣候變遷日益嚴峻，極端氣候事件如乾旱與洪澇頻仍，對農業生產構成前所未有的挑戰。臺灣雖然全年降雨量豐沛，但雨量分布極不均，乾濕季明顯，加上地形起伏與部份農地分散，導致農業灌溉與排水系統負擔沉重。為提升糧食自給率與水資源效率，臺灣的現代化農業系統需導入更科學化、系統化的水土管理技術。

本研究針對中國黃河流域河套灌區（Hetao Irrigation District, HID）所進行地下排水系統（Subsurface Pipe Drainage, SPD）的虛擬模擬分析，為管理人員制定了 SPD 設計的指導方針，例如整個灌區 SPD 的使用，可提供一定程度的參考。

地下排水系統 (SPD) 是指埋設於地表以下的排水管網，藉以排除多餘的土壤水分，維持根系氧氣充足，改善作物生長環境。此系統過去多用於低漥積水地或鹽鹼地改良，但隨著灌區管理精細化，越來越多研究開始評估 SPD 在乾旱或半乾旱地區的應用價值。本研究根據目前的模擬分析結果，對哪些地區更適合安裝地下管道提出了一些建議。提供了臺灣農業升級的一個重要啟示——即藉由優化的 SPD 系統配置，結合作物分區調整，可顯著提升作物產量與水分生產率（Water Productivity, WP），甚至開發具有潛力耕地。

在該項針對 HID 的研究中，研究團隊透過整合 SWAP-WOFOST 模型，分析不同地下管線配置對於作物產量、水分利用效率的影響，結果顯示：適當設計 SPD 後，春小麥、春玉米與向日葵年平均產量分別提升 19%、7%、11%；而水稻則提升 13%、5%、10%，不僅產量增加，水資源利用效率亦隨之改善。此外，透過優化灌區末端水路以及排水設施，可望新增約 3,489 公

頃耕地。這種「以水控田、因地制宜」的灌排系統規劃理念，為同樣面臨農地資源緊張的臺灣提供了一個借鏡。

SPD 技術對臺灣農業的啟示及可能帶來的應用潛力與改善效益，探討如下：

1. 提升水管理效率

SPD 能有效排除土壤中多餘水分，避免積水導致根腐與減產，對於北部與西部地勢低窪地區以及靠近河川公地周邊的農田亦可能是排水不良的區域尤其有利。同時，透過地下排水的導引與再利用（如回收再灌溉），也能提升整體水資源循環效率，減少水資源浪費。

2. 優化作物種植分區與輪作制度

透過結合 SWAP-WOFOST 等模擬工具，可進行不同作物對水分需求的空間規劃與輪作模式設計。例如在南部乾燥地區規劃耐旱作物（如玉米、甘薯），在有良好 SPD 設施的區域則種植需水較高作物（如水稻、蔬菜）。此舉不僅可減少用水衝突，也提升單位水資源產出效益。

3. 釋放閒置與不利耕作土地

根據 HID 案例，改良末端溝渠系統可轉為可耕地，對臺灣農村出現的「農地撂荒」現象具重要參考價值。許多農地因排水不良或設施老舊，長期閒置，若能透過 SPD 與整田技術改善，將有助於恢復生產能力，進一步穩定糧食供應。

4. 減少化肥與農藥流失，保護環境

良好的地下排水系統可減少地表逕流帶走化肥與農藥進入河川，降低水質污染風險，有助於達成農業綠色永續發展的政策目標。

臺灣農業的未來，需要更多像 SPD 這樣的科技與策略加持，從根本改善耕作環境，為下一代打造更穩健的糧食生產體系，要在臺灣推動 SPD 應用，除了技術本身的移轉與在地化改良外，更需要整體制度與政策的配合，主要的方針羅列如下：

1. 加強農業水文模擬技術應用：

政府可與學研單位合作，建立適用於各縣市農業區域的模擬模型，評估 SPD 與作物種植互動關係。

2. 補助與推廣在地化 SPD 建設：

針對地勢低窪、排水不良區域提供補助，鼓勵農民建置地下排水系統，並搭配農田整備與灌溉設施升級。

3. 推動數位農業與智慧灌排系統：

將 SPD 系統結合感測器、IoT 技術，即時監控田間水位與排水狀況，提升管理效率。

4. 整合農地整備與區域規劃政策：

配合區域農業發展規劃，結合 SPD 技術進行整地與種植分區，落實「一地一策」。

本研究針對 HID 所提出的 SPD 佈局優化策略，不僅提升了作物產量與水分生產率，亦展示了結合模擬模型與實地規劃的強大潛力。對臺灣而言，這是一個極具啟發性的案例。面對農業轉型與氣候調適的雙重壓力，導入地下排水系統作為基礎農業基礎設施升級的一環，不僅可提高水資源效率與耕地利用率，更有助於實現永續農業與糧食安全的雙重目標。

摘要翻譯及註解：劉日順 研究員

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Simulating the impact of subsurface pipe drainage systems on crop water productivity at a regional scale in the upper Yellow River Basin

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ABSTRACT

Subsurface pipe drainage (SPD) could provide a suitable environment for crop production in arid and semi-arid agricultural areas; however, less attention has been given to the design layout of SPD on the regional scale in Hetao Irrigation District (HID). In this study, the appropriate layout of the final subsurface pipe was determined using the distributed SWAP-WOFOST (Soil–Water–Atmosphere–Plant and WORld FOod STudies) model in HID. Subsequently, the impact of the proper SPD on crop yield and water productivity (WP) were evaluated. Finally, the crop zoning was adjusted to further enhance crop WP, and the corresponding newly added cultivated land area was preliminarily estimated based on the suggested SPD. The results indicated that after zoning in the suggested SPD, the annual average yields of spring wheat, spring corn and sunflower increased by 19%, 7% and 11%, respectively, and WP improved by 13%, 5% and 10%, respectively, compared to the traditional layout. The newly added cultivated land area was estimated to be approximately 3489 ha through the replacement of traditional end ditches with subsurface pipes in HID. Therefore, the suggested subsurface pipe designs and cropping pattern adjustment improved crop growth and led to an increase in the cultivated land area in HID.

KEYWORDS

crop zoning, distributed SWAP-WOFOST model, groundwater depth, subsurface pipe drainage, water productivity

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人工神經網路在 Manipur, India 的 Loktak 灌區雨量時間序列 預測之應用

Satish Yumkhaibam, Bharat C. Kusre

摘要

主要的灌溉與其他農業活動用水來源是降雨，降雨會立即影響作物的生長與生產力。若能事先預測降雨，農民便可有效規劃作物種植模式。近年來，由於計算技術的進步，降雨預測成為熱門研究主題。人工神經網路(ANN)就是其中一種被廣泛應用於降雨預測的技術。由於其非線性資料學習方式，ANN 模型能提供更準確的預測，因此更具可靠性。本研究中所建立的 ANN 模型，目的是預測全年、季風期與季風後期的降雨量。該模型以印度曼尼普爾邦 Loktak 提水灌溉計畫區域內從 1985 至 2018 年的 34 年資料進行訓練，並採用修正線性單元 (ReLU) 作為啟動函數。以三年期資料作為輸入的模型在各季節中表現皆優，其中最佳模型的判定係數 (R^2) 為 0.36、均方根誤差為 75.7、相關係數為 0.60、平均絕對誤差為 62.5。這些表現指標與其他研究者的結果相當，因此該模型可應用於此研究區域。

關鍵字：啟動函數、人工神經網路、Python 程式設計、降雨預測

註解

這篇文章由 Yumkhaibam 和 Kusre 於 2023 年發表，旨在探討如何應用人工神經網路 (ANN) 進行降雨時間序列預測，以協助印度曼尼普爾邦洛克塔克提灌區的農業水資源管理。

雨量是農業灌溉的主要水源，直接影響作物生長與產量，但其時間與空間的不確定性使得資源規劃變得困難。在印度，特別是依賴季風雨的地區，準確預測雨量有助於農民規劃作物輪作、減少乾旱或洪水的損害。傳統統計方法在資料量大時的預測效果有限，因此本文嘗試以人工神經網路這類非線性資料學習工具來提升預測準確度。

研究地點位於印度東北部的曼尼普爾邦，涵蓋 Loktak Lift Irrigation Project (LLIP) 指定灌溉區域，該區為全州最大灌溉計畫，面積約為 0.0234 Mha。研究使用 1985 至 2018 年共 34 年的日雨量資料，來自 Imphal 的印度農業研究委員會 (ICAR) 氣象站。

研究首先處理缺漏值與檢查資料同質性 (homogeneity)，採用移動平均法平滑非同質性資料，並進行 min-max 正規化，使資料落在 0~1 之間，有利於 ANN 模型的訓練。

在建模過程中，使用三種時間序列類型進行降雨預測：年降雨量 (annual)、季風期 (6~9 月)、季風後期 (11~3 月)，每一類型都採用多種不同架構的 ANN 模型進行測試。所有模型皆使用 ReLU 為啟動函數，Adam 為最佳化器，訓練次數 (epoch) 為 30，批次大小 (batch size) 為 2。模型在 Google Colab 上以 Python 建構，使用多個套件如 NumPy、Keras、scikit-learn。

結果指出，輸入三年期雨量資料的模型 (3-8-1 與 3-5-1) 整體表現最佳，這些結果與其他地區類似研究的預測表現相當，顯示該 ANN 模型在本地區具有實用性。

本研究證明，基於 ANN 的降雨預測模型可應用於洛克塔克灌溉區不同季節的雨量預測，並具有實務應用潛力。未來建議可探索更多氣象變數的

混合模型或加入空間資料，以進一步強化預測能力。

摘要翻譯及註解：胡明哲 教授

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**Application of artificial neural networks for time series rainfall forecasting
in the Loktak lift irrigation command area of Manipur, India**

Satish Yumkhaibam, Bharat C. Kusre

ABSTRACT

The primary source of water for irrigation and other agricultural activities is rainfall. It has an immediate effect on crop growth and productivity. Forecasting this rainfall in advance allows farmers to effectively plan their cropping pattern. In recent years, forecasting rainfall has become very popular due to the availability of the latest computation techniques. Artificial neural networks (ANNs) are one such technique widely used for rainfall prediction by a number of researchers. These models are more reliable as they make better predictions because of their nonlinear data learning method. In the present study, an ANN model was developed to predict the annual, monsoon and postmonsoon season rainfall. The model was developed using 34 years of data from 1985 to 2018 in the command area of the Loktak Lift Irrigation Project in Manipur, India. The ANN model was trained using the rectified linear unit (ReLU) activation function. The 3-year input model excelled in all seasons, with the best model achieving a 0.36 coefficient of determination (R^2), 75.7 root mean square error, 0.60 correlation coefficient and 62.5 mean absolute error. These performance indicators were comparable with studies performed by other researchers. Thus, the model can be adopted for the study area.

KEYWORDS

activation function, artificial neural network, Python programming, rainfall forecasting

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新型旋轉-線性移動式精密灌溉設備之性能評估

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摘要

隨著人口持續增長，全球淡水資源日益匱乏，農業用水已成為限制糧食生產的重要因素之一。可變率灌溉(Variable-rate irrigation, VRI)作為精準灌溉技術的一種，能有效提升用水效率，確保作物獲得最適水分供應。在匈牙利，德布勒森大學(University of Debrecen)與 Magtár Kft. 公司合作，率先開發出一種配備 VRI 技術的新型橫向移動式灌溉機。本研究即針對該系統進行測試與評估；研究結果顯示，實際操作中可達到高水準且均勻的灌溉效果，其 Christiansen 均勻係數(CUc%)為 93 ± 2 、分佈均勻度(DU%)為 88 ± 2 、變異係數(CV)為 9 ± 2 ；灌溉準確度亦表現良好，平均絕對誤差(mean absolute error)為 0.6 ± 0.1 、平均偏誤(mean bias error)為 0.2 ± 0.2 、標準化均方根誤差(normalized root mean square error)為 8.6 ± 2 。此外，灌溉過量與不足的比例亦相對較低，僅有 $1.4\% \pm 2\%$ 的區域灌溉過量、 $0.4\% \pm 0.3\%$ 的區域發生灌溉不足的現象。本研究進一步分析沿灌溉管線不同管理區的灌溉均勻性與準確性，結果發現各區域的灌溉水深存在顯著差異($p < 0.05$)。綜上所述，配備可變率灌溉(VRI)技術的新型橫向移動灌溉設備，未來可應用於可耕地區域，藉以制定更具均勻性與準確性的灌溉排程，對於實現節水型灌溉管理具有關鍵意義。

關鍵字：灌溉準確性、灌溉均勻性、線性灌溉系統、可變率灌溉

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註解

隨著全球人口預計於 2050 年突破 95 億，面對農業、都市與工業用水需求持續上升的壓力，特別是在乾旱與半乾旱地區，水資源的缺乏日益成為糧食生產的主要瓶頸之一。因此，如何推動灌溉技術革新以應對氣候變遷與土地空間異質性，已成為全球農業水資源治理的重要課題。本篇研究聚焦於全球水資源日益緊張的背景下，如何透過精準灌溉技術提升農業用水效率，為水資源管理與農業生產尋求兼顧效率與永續的解方。

本研究由匈牙利德布勒森大學與 Magtár Kft. 技術公司共同合作，開發並測試匈牙利境內首座配備可變率灌溉技術(Variable Rate Irrigation, VRI)的新型旋轉-線性移動式精密灌溉設備，其為中東歐地區在灌溉機械化與智慧化技術領域的重要創新。此灌溉系統具備獨特的旋轉與線性並行行進能力，可依據地塊差異進行灌溉量調節，以期達到更高的灌溉均勻性與水資源利用效率。為評估新型旋轉-線性移動式精密灌溉設備之性能及適用性，本篇研究採用田間試驗方式，於匈牙利東北部一處面積達 85 公頃、主要種植玉米之可耕地進行實測，試驗時間為 2020~2021 年。研究設計涵蓋三大類測試：格網測量、縱向轉換測試，以及不同管理區域的灌溉精度評估。使用多達 118 個噴頭與接水桶布設網格，並透過模擬 2.5~10 mm 等不同灌溉深度之情境，分析灌溉均勻性指標(包含 Christiansen 均勻性係數 $CUC\%$ 、分佈均勻度 $DU\%$ 、變異係數 CV)，並評估準確性指標如平均絕對誤差(MAE)、平均偏誤(MBE)與標準化均方根誤差(NRMSE)。

本篇論文之研究結果顯示該設備在實際操作中具備極佳的灌溉均勻性與精準性；其中在模擬固定灌溉深度(10 mm)之格網測試中， CUC 高達 95 %、 DU 為 91 %， CV 僅 6 %，顯示其灌溉效果高度一致且變異性低。在不同試驗區的應用測試中，依據不同灌溉比例(25~100%)調控區域性灌溉深度，4 個測區均能精確達成設定目標，最高誤差(MAE)亦僅 0.8 mm。此外，研究也指出在灌溉機移動方向上的區域轉換寬度約需 12 m，作為規劃變水量

灌溉區域邊界設定之參考依據。

本篇研究開發的新型旋轉-線性移動式精密灌溉設備具備幾項值得學習的創新性，包含：1.技術層面的整合創新，為匈牙利首度導入旋轉式線性灌溉結構結合可變率控制技術，並透過 GPS 精準定位與電磁閥區塊管理，有效解決傳統灌溉設備無法區域調控的限制。2.該研究提出可量化評估灌溉均勻性與準確性的標準指標體系，並導入田間格網與縱向測線等佈局，有助於後續同類型系統的測試與比較。3.實務層面透過多次實地試驗證實其系統穩定度與調控能力，為精準農業提供具高度實用性的技術解方。

進一步從政策觀點來看，本篇研究對台灣農業與水資源管理具有以下幾點啟發意義及參考價值：

1.促進灌溉區位管理與精準施灌：台灣地形複雜、灌溉事業區外的耕地分布破碎，採用傳統灌溉方是難以兼顧均勻性與用水效率。若能引進此類 VRI 技術，搭配農地灌溉範圍分區與感測數據，即可因地制宜地調整灌溉量，有效減少過度灌溉導致的資源浪費或作物歉收。

2.導入智慧農機設備政策誘因：本研究顯示在 VRI 結 GPS、電磁閥與主控台的條件下，能達到高精度的灌溉控制。國內農政單位在預算允許的前提下，可考慮擴大智慧農機補助的額度及設備種類，以鼓勵農民導入節水型灌溉系統。

3.建構本土灌溉均勻性標準體系：目前國內尚無針對智慧灌溉設備建置明確評估準則與標準；本篇論文所使用的灌溉效益指標(CUc%、DU%、CV等)，可作為擬定灌溉設施驗收與補助標準之參考依據。

綜上所述，本篇研究不僅展現了技術整合與試驗設計的高度成熟性，亦透過田間實證驗證其可行性，為精準灌溉的推廣應用奠定了實務基礎，對於推動農業智慧化與資源永續具高度借鏡價值。建議未來台灣可朝向建立適地適作之灌溉分區策略、灌溉精準管理平台與智慧農業機具補助政策，加速邁向節水、高效與環境友善的農業體系。

摘要翻譯及註解：陳豐文 研究員

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Evaluation of new pivoting linear-move precision irrigation machine

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ABSTRACT

Due to population growth, freshwater resources around the world are becoming increasingly scarce, and the water supply in agriculture has emerged as one of the limitations of food production. Variable-rate irrigation (VRI), a type of precision irrigation, allows water-efficient irrigation techniques to ensure an optimal water supply. The University of Debrecen, in collaboration with Magtar Kft., was the first in Hungary to develop a new laterally mobile irrigation machine equipped with VRI. The subject of our study was the testing of this system. According to the research, high and homogeneous irrigation uniformity was achieved in practice, with a Christiansen uniformity coefficient (CUC%) of 93 ± 2 , distribution uniformity (DU%) of 88 ± 2 and coefficient of variation (CV) of 9 ± 2 . Irrigation accuracy was also found to be satisfactory (mean absolute error 0.6 ± 0.1 , mean bias error 0.2 ± 0.2 , normalized root mean square error 8.6 ± 2), and only $1.4\%\pm 2\%$ was over-irrigated and $0.4\%\pm 0.3\%$ under-irrigated. In addition, the uniformity and accuracy of irrigation in different management zones along the pipeline were also investigated, and significant differences ($p<0.05$) were found between irrigation water depths. Based on the above, a new laterally mobile irrigation machine equipped with VRI can be used to develop more uniform and accurate irrigation schedules in the future in arable fields as this is critical for water-saving irrigation management.

KEYWORDS

irrigation accuracy, irrigation uniformity, linear irrigation system, variable rate

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物聯網架構下的精準農業智慧滴灌系統開發

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摘要

精準灌溉排程透過即時感測器的應用，有提升用水效率，同時最大化資源利用率的潛力。傳統農業因不適的資源管理而受到不利影響，為了減輕農民的負擔，本研究開發並測試了一套基於物聯網 (IoT) 的滴灌系統，並評估其系統效能。該系統與基於作物蒸散量 (ETc) 的滴灌系統進行比較，作物為種植在含黏土量較高的育苗床中的茄子。

此開發系統包含感測器與微控制器，可記錄環境參數，包括土壤含水量、土壤溫度、相對濕度與空氣溫度。灌溉排程根據上限 (田間容水量) 與下限 (植物可用水量的 50%) 進行設定。當土壤濕度降至下限 (33%) 時啟動灌溉，當回升至田間容水量 (46%) 時結束灌溉。

感測器收集的資訊透過物聯網技術無線上傳至雲端伺服器，全球任何地點皆可存取。實驗觀察顯示，使用物聯網滴灌系統的茄子植株比使用 ETc 滴灌系統的植株高出 1.3 公分，其葉片長度與寬度也優於 ETc 的滴灌系統。與 ETc 系統相比，IoT 系統提升了輸水馬達的效率，使其運作時間減為 85 分鐘，亦分別增加植株葉片長度與寬度為 4.4 公分與 3.1 公分，而 ETc 系統則為馬達需運作 125 分鐘、植株葉片長度與寬度僅為 3.7 公分與 2.4 公分。

在 31 天的試驗期間，IoT 滴灌系統較 ETc 系統節水達 35%。此外，所開發的系統堅固耐用，並配備防水外殼，適合用於戶外農田。

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關鍵字：自動灌溉，ESP 32，土壤濕度，物聯網，水分利用效率

註解

面對氣候變遷、農業用水競爭與人力短缺的多重挑戰，臺灣農業亟需導入創新技術以提升水資源利用效率與作物生產穩定性。尤其在水資源配置日益緊張的今天，「如何聰明用水、如何智慧生產」已成為臺灣農業能否永續發展的關鍵。本研究以物聯網（Internet of Things, IoT）技術為基礎的滴灌系統，顯示出透過即時感測器所驅動的灌溉排程，在節水與增產方面具有顯著潛力，為臺灣智慧農業建設提供了具體方向與實證基礎。

臺灣農業用水早期依賴渠道輸送與人工操作，常見的漫灌、溝灌方式雖操作簡便，但水分利用效率低落，常導致過度灌溉、地力耗損及地下水位不穩定等問題，目前雖已陸續推動遠端監控系統，但僅能設置於重點區域，尚無法普及。此外，農業勞動力老化，使得農民難以依據每日天候與土壤狀況即時調整灌溉策略，導致水資源管理缺乏彈性與準確性。為提升農業灌溉智慧化程度，有效整合感測、控制與雲端管理的系統成為發展重點。而本研究以精準滴灌技術的研究成果與亮點，可為臺灣的未來發展提供有利的借鏡。

本研究設計了一套基於物聯網的自動滴灌系統，透過安裝於田間的感測器與微控制器，能夠即時監測包括土壤濕度、土壤溫度、相對濕度與空氣溫度等關鍵環境參數。當感測器偵測土壤濕度低於設定下限（33%）時，自動啟動灌溉；濕度回升至田間容水量上限（46%）則自動停止灌溉，實現精準而節能的灌溉排程。該系統還具備以下幾項顯著優勢：

1. 資料即時上傳至雲端：無論身在何處，農民皆可透過手機或電腦掌握田間狀況。
2. 植株生長改善：使用 IoT 灌溉系統的茄子植株在高度、葉片長與寬度等指標，皆優於傳統 ETc（作物蒸散量）控制系統。
3. 節能與節水效益明顯：IoT 系統灌溉所需馬達運作時間較 ETc 少 40 分鐘，節水高達 35%，並有效提升作物葉片發育。
4. 設備穩固耐用：感測器與控制系統防水設計，可應對臺灣多雨與潮濕氣

候，提升戶外應用的可行性。

5. 良好成效顯示：IoT 灌溉系統不僅能節省水與電資源，還能促進作物健康發展，對經濟、生態與節能減碳皆具正面影響。

近年臺灣中南部頻繁出現春季乾旱，農業灌溉限水已屢見不鮮。此研究所展示的自動化滴灌系統能在水源有限的情況下，根據實際需求精準灌溉，避免水分浪費，為水情吃緊的農區提供了有力的調適工具。此外，由於農村人口老化，農民人力不足，難以每日巡視田間。IoT 系統的自動啟停與遠端監控功能，能減輕人力需求，尤其適合單人經營或缺乏農業專業知識的小農戶，促進「一人也能經營」的智慧農場發展。尤其搭配滴灌系統，可促進設施園藝與高經濟作物生產，滴灌系統特別適合在溫室、育苗場或園藝作物田中應用，如花卉、茄科蔬果（如茄子、番茄）等。臺灣此類高附加經濟價值作物面積日益增加，結合感測系統可大幅提升產值與品質穩定性，並減少病蟲害發生。此外，採用相關系統作為農業經營的灌工具，可促進農業減碳與永續轉型，節能、節水即是減碳。透過減少灌溉馬達的運作時間，這套系統降低能源消耗與碳排放，有助於實現農業部推動的「淨零農業」願景。

為加速此類智慧農業技術於臺灣普及，政府與民間可從下列幾個面向推動並擬定政策建議與推廣方向：

1. 建立農業 IoT 應用示範區：由農業部主導，選定不同氣候帶與作物類型的農場，推動試點計畫，並蒐集長期數據作為推廣依據與政策評估工具。
2. 補助智慧灌溉設備安裝：針對設施農業、小型農戶、青年農民等群體，提供 IoT 滴灌系統的購置與安裝補助，降低導入門檻。
3. 開發簡易操作平台與教育資源：設計適合臺灣農民使用的介面，並結合農會、農改場開設課程，培養智慧農業人才。
4. 整合灌溉數據至區域農業管理平台：結合天氣預報、水情資訊與感測資料，發展區域型農業決策支援系統，推動農業「數位治理」。

本研究開發的基於物聯網的自動滴灌系統，不僅具備高度節水與增產的優勢，更符合臺灣農業對「智慧、永續、高效」三大目標的長遠需求。在

氣候壓力與資源限制下，灌溉不再只是「澆水」這麼簡單，而是一門講求資料、精度與即時反應的現代農業科學。臺灣農業若能把握這類技術創新契機，結合政策與產業力量，不僅能提升產量與品質，更能在全球糧食與環境壓力中找到韌性發展的道路。

～滴水之間，藏著農業升級的關鍵!～

摘要翻譯及註解：劉日順 研究員

財團法人農業工程研究中心

Development of a smart IoT-based drip irrigation system for precision farming

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ABSTRACT

Precision irrigation scheduling using real-time sensors has the potential to boost water use efficiency while maximizing resource utilization. Traditional farming is adversely affected by improper resource management. To overcome a farmer's efforts, an IoT-based drip irrigation system was developed and tested for system performance. It was compared with an ETc-based drip irrigation system for brinjal crops grown in planter beds filled with vertisols. The developed system, consisting of sensors and microcontrollers, records the environmental parameters, namely, soil moisture content, soil temperature, and relative humidity and temperature. Irrigation scheduling was programmed using upper (field capacity) and lower thresholds (50% plant available water). Irrigation applications were triggered when the soil moisture value reached the lower threshold (33%) and ended after the field capacity was attained (46%). The information captured by the sensors is wirelessly uploaded to the cloud server using IoT technology, which can be accessed from anywhere in the world. It was observed that the IoT-based drip irrigation testing plant grew 1.3 cm taller than the ETc-based drip irrigation testing plant. The length and width of brinjal plant leaves also increased more than the ETc-based drip irrigation treatments. The IoT-based drip irrigation treatments improved pump operating time, leaf length and width by 85 min, 4.4 cm and 3.1 cm, respectively, compared to 125 min, 3.7 cm and 2.4 cm for the ETc-based drip irrigation treatment. During a period of 31 days, water savings of 35% were observed compared to ETc-based drip irrigation. The developed system was rugged, and a water-resistant enclosure allowed its use in outdoor agriculture fields.

KEYWORDS

Automatic irrigation, ESP 32, soil moisture, ThingSpeak, water use efficiency

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梨果仙人掌(*Opuntia ficus-indica*)飼料作物於伊朗克爾曼之 乾旱環境下灌溉最佳化研究

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摘要

水資源短缺與乾旱是伊朗畜牧業面臨的主要挑戰，因其導致飼料供應短缺。仙人掌植物在 2017 至 2019 年間進行了三年的農藝性狀與水生產力研究。研究採用四次重複的隨機區組設計。2017 年施行了正常、適度乾旱壓力與嚴重乾旱壓力三種灌溉處理。對仙人掌植物所用的灌溉水深是根據累積蒸發皿蒸發量：2017 年為 100、140、180 毫米；2018 年為 140、190、240 毫米；2019 年為 160、210、260 毫米，這些數值代表每次灌溉總水深。

在 2018 與 2019 年中，正常與嚴重乾旱壓力處理下，每株植物所產生的莖節數(cladodes)分別為最多與最少。隨著乾旱壓力增加，莖節長度、寬度與直徑皆呈下降趨勢。嚴重乾旱壓力下的產物鉀含量最高，而中洗纖維(NDF)酸洗纖維(ADF)濃度則為最低。在 2018 與 2019 年，正常灌溉對水生產力的影響最大。正常灌溉的新鮮與乾燥後產量最高(2018 和 2019 年溼重為每公頃 57.3 與 112 公噸；乾重則為每公頃 4.51 與 8.97 公噸)。在輕度乾旱壓力下，粗蛋白含量為 8%；而在嚴重乾

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旱壓力下則為 7%。研究結果顯示，在伊朗克爾曼地區，可以使用較少的水資源種植仙人掌。

關鍵字：農藝性狀、仙人掌、乾旱壓力、飼料、水分生產力、產量

註解

在伊朗等乾旱與半乾旱地區，牲畜飼養是農業重要的一部份，不僅影響糧食安全，也關係農民收入與鄉村發展。然而，頻繁的乾旱與水資源匱乏導致飼料作物生產大幅減少，直接衝擊畜牧業的生產。而梨果仙人掌(*Opuntia ficus-indica*)因具備耐旱、耐貧瘠土壤及高水分儲存能力，被視為理想的替代飼料作物。仙人掌已在世界多國如巴西、墨西哥與南非廣泛種植，具備高碳水化合物、抗壞血酸與礦物質(尤其是鈣)含量，並能作為牛、羊、山羊等的飼料來源。過去研究指出，仙人掌生產每公斤乾物質(dry matter)所需用水為 267 公升遠低於其他飼料作物，其水分生產力顯著高於其他作物。本研究目的在於評估不同乾旱灌溉處理下，仙人掌在伊朗克爾曼地區的生長表現、水分利用效率與營養成分變化，為當地乾旱條件下的飼料生產提供實證依據。

研究自 2017 至 2019 年在克爾曼省 Shahmaran 研究站進行，採用隨機區組設計，共有三種灌溉處理：正常灌溉、中度乾旱與嚴重乾旱。三年中各灌溉量依當年度累積蒸發皿蒸發量調整水量，2017 年為 100/140/180 mm，2018 年為 140/190/240 mm，2019 年為 160/210/260 mm。試驗共重複 4 次，每年在灌溉過程中皆使用土壤水分感測器與重量法監測根區土壤含水量，確保灌溉至田間持水量。

植株採用來自突尼西亞的仙人掌葉狀莖(cladode)進行繁殖，每塊試驗地種植 30 株，種植間距為行距 2 公尺、株距 1.5 公尺。施肥管理包含氮肥與磷肥，在三年間依據植株年齡遞增施用量。灌溉採滴灌系統，逐年增加每株滴灌滴頭數量。每次灌溉皆以測得之田間水分與根深為基準計算需補充水量，並記錄每處理下的水用量。

農藝與品質測量包括每株葉狀莖(cladode)數量、長度、寬度、直徑、鮮重、乾重、粗蛋白(Kjeldahl 法)、中/酸洗纖維(NDF/ADF)及鉀鈉離子含量(火焰光度法)。每年數據分別分析變異並以 LSD 法檢定差

異。

在 2017 年試驗初年，因前五個月皆以標準灌溉促進生根，因此三種處理間的葉狀莖生長無顯著差異，平均每株產出 5.7 個葉狀莖。自 2018 年起，灌溉差異明顯影響植株表現：正常灌溉下每株產出葉狀莖數達 22.5(2018)與 27.8(2019)，顯著高於嚴重乾旱處理(分別為 16 與 15 個)。葉狀莖長、寬與直徑在乾旱條件下明顯下降，表現出皺縮與厚度減少的生理反應。

2018 與 2019 年正常灌溉處理下的鮮重與乾重分別為：57.3 與 4.51 噸/公頃(2018)；112 與 8.97 噸/公頃(2019)，遠高於中度與嚴重乾旱灌溉處理。此外，雖乾旱限制了產量，但嚴重乾旱處理下的葉狀莖鉀含量最高，而 NDF 與 ADF 濃度最低，顯示其粗纖維含量下降；蛋白質含量在中度乾旱下為 8%，嚴重乾旱時降為 7%。從根系觀察結果來看，根系橫向擴展與縱深逐年增長，顯示植株具有適應乾旱條件的根系結構擴張能力。

本研究證實仙人掌可在克爾曼乾旱地區作為高效節水型飼料作物。雖嚴重乾旱明顯抑制葉狀莖產量與形態發展，但仙人掌在中度乾旱條件下仍保有不錯的產量與營養價值，水分利用效率顯著高於傳統作物。結果指出，在資源有限地區，合理灌溉管理與施肥搭配下，仙人掌不僅可減少畜牧業對水資源的依賴，並緩解飼料短缺問題。建議未來在乾旱地區推廣仙人掌飼料生產，並透過品種改良與種植模式優化進一步提升其生產潛力與營養價值。

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Optimizing irrigation for cactus (*Opuntia ficus-indica*) fodder production under drought conditions in Kerman, Iran

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ABSTRACT

Water scarcity and droughts are major challenges for cattle production in Iran due to the resulting feed shortages. Cactus plants were studied for 3 years (2017–2019) for their agronomic and water productivity. The study used a four-replication randomized block design. Normal, moderate drought stress and severe drought stress irrigation were applied in 2017. The irrigation depths applied to the cactus plants were established by referencing cumulative pan evaporation values, with 100, 140 and 180 mm in 2017; 140, 190 and 240 mm in 2018; and 160, 210 and 260 mm in 2019, representing the total depth of water added during each irrigation event. In 2018 and 2019, the normal and severe drought stress treatments produced the most and least number of cladodes per plant, respectively. As dry stress increased, the cladode length, breadth and diameter decreased. Severe drought stress had the greatest potassium content and the lowest neutral detergent fibre (NDF) and acid detergent fibre (ADF) concentrations. Normal irrigation had the greatest effect on water productivity in 2018 and 2019. The usual treatment produced the greatest fresh and dry yields in 2018 (57.3 and 4.51 t ha⁻¹) and 2019 (112 and 8.97 t ha⁻¹). Under mild drought stress, the crude protein content was 8%, and under severe drought stress, it was 7%. The results suggest that Kerman, Iran, can grow cactus with less water.

KEYWORDS

agronomic characteristics, cactus, drought stress, fodder, water productivity, yield

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透過評估智利中部葡萄園土壤水平衡評估 潛在灌溉水節水量

Oswaldo Salazar¹, Marcela Castro², Ranvir Singh³, Helena Ponstein⁴

摘要

本研究的主要目的是透過評估智利馬烏萊大地區葡萄園生長季的土壤水平衡，評估灌溉水潛在節水效益。研究旨在深入瞭解不同灌溉水應用對於土壤水分情形的影響，以及其對葡萄產量、水分利用效率（water use efficiency, WUE）與灌溉成本的潛在影響，以協助改善當地與其他類似地中海地區的灌溉方法。本田間實驗比較三種灌溉水量應用：現行灌溉水量（T0）以及兩種缺水灌溉處理，分別是減少至75%（T1）以及減少至50%（T2）。測量項目包含整個生長季（2017年10月至2018年4月）期間之土壤體積含水量、淺層地下水位、樹冠覆蓋度以及葡萄產量。我們發現，在維持葡萄產量、提高WUE與降低灌溉成本的同時，現有灌溉系統可減少25%或50%的用水量。考慮冬季降雨累積之土壤儲水量以及淺層地下水毛細管上升的可能性，對於根據葡萄樹的需水量調整灌溉至關重要。

關鍵字：散裝葡萄酒、節水灌溉、土壤含水量、水分利用效率

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註解

以作物生長期間之土壤水平衡情形評估灌溉水量灌溉，可在維持作物產量之情況下達到節水效果，以更適度之灌溉水量灌溉，避免水資源浪費。本研究以地中海型氣候代表作物葡萄作為研究目標，進行田間試驗，以不同灌溉程度相互比較，影響之關鍵因子包含土壤水力特性(物理特性、水文特性、葡萄生根深度、土壤濕度與地下水位)、作物(蒸發散量、樹冠覆蓋度、可溶性固體、密度、酸鹼值、總酸度以及產量)、灌溉時機，並量測土壤含水量，用以作為作物需水量及灌溉量評估依據，並利用 WUE 可量化灌溉成效。

台灣作物多樣性高，且有如水稻等須大量灌溉水之作物，若能以水平衡角度，參考本研究之評估方法，因地制宜，以適宜各作物需水量，考量環境因子，調整灌溉水量，在不減少作物產量下，達到節約水資源效果，將產生更大經濟效益且能有更多餘裕調配水資源。

除地表水之灌溉外，地下水抽取也是主要灌溉水源之一，地下水抽取有經濟成本(勞動力、設備等)，且若長期超抽地下水可能導致地層下陷，引發災害，在節約灌溉水量後，可減少下水抽取量，降低經濟成本與其他機會成本，以台灣地區而言，平原農地多位於沿海地區，長期超抽地下水導致之地層下陷，面臨颱風及大潮等氣與海象事件，可能產生海水倒灌情形，造成巨大損失。

更換灌溉設備並根據土壤溼度調節灌溉量也能節約灌溉用水，例如將滴灌管更換為流量較小者，並部屬相關儀器設備監測土壤水分含量，適時適量灌溉，有助於節約灌溉用水。

本研究提供評估節約潛在灌溉用水之方法，台灣作物多元，地形地質型態多變，若能因地制宜，適度適量為各作物提供最佳灌溉方法，將能維持產量並節省灌溉水資源，抽取地下水者，更能預防地層下陷帶來之災害。

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Evaluation of potential irrigation water savings by assessing the soil water balance in a vineyard in central Chile

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ABSTRACT

The main aim of this study was to evaluate the potential savings of irrigation water by assessing the soil water balance during the growing season in a wine vineyard in the Maule region, Chile. This study provides insights into the influences of different irrigation water applications on soil water status and its potential effects on grape yields, water use efficiency (WUE) and the cost of irrigation to help improve irrigation practices in the region and other similar Mediterranean regions. The field experiment compared three levels of irrigation water applied: current irrigation of the vineyard (T0) and two deficit irrigation treatments with reductions to 75% (T1) and 50% of the irrigated water (T2). The measurements included volumetric soil water content, shallow groundwater table, canopy cover and grape yield at harvest during the entire growing season (October 2017 to April 2018). We found a potential reduction of 25% or 50% in the current irrigation system while maintaining the grape yield, increasing the WUE and reducing the cost of irrigation. Consideration of the water stored in the soil by the accumulation of rainfall in the winter season and the potential for capillary rise of shallow groundwaters is crucial for adjusting irrigation to vine water requirements.

KEYWORDS

bulk wine, deficit irrigation, soil water content, water use efficiency (WUE)

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根據監測與預測的乾旱情況之最適作物種植模式 與用水量配置

Farzaneh Khajehi, Mohammad Mehdi Moghimi, Abdol Rassoul Zarei

摘要

農業部門的乾旱管理需要對乾旱現象進行監測與預測，並提供合適的作物種植模式。在本研究中，採用偵察乾旱指數（RDI）來監測伊朗法爾斯省的乾旱情況。透過匹配 RDI 時序資料與地下水位資料的模型，預測當地水資源的狀況。依據預測的可用水資源，利用遺傳演算法求得最適作物種植模式。整體而言，實際與預測的地下水位變化顯示研究區域的地下水資源正處於嚴峻狀態。為了減少地下水資源的消耗，應推行節水灌溉方案，將對水分缺乏較不敏感的作物（如大麥、小麥、油菜、飼料玉米和馬鈴薯）納入種植模式中。作物種植模式最佳化結果顯示，由於北部地區年降雨分布較佳、水資源狀況相對良好，應增加當地較具經濟效益作物的種植面積。然而，隨著用水成本上升，這些作物的種植面積及其最佳減水比例均有所下降。

關鍵字：作物種植模式、乾旱預測、最佳化、用水量、水量減少比例

註解

本研究旨在於乾旱頻仍的伊朗 Fars 省，建構一套基於乾旱監測與預測的作物種植模式與地下水利用策略，以因應氣候變遷下水資源日益短缺的挑戰。研究使用「偵測乾旱指數 (RDI, Reconnaissance Drought Index)」進行年度乾旱監測，並透過 RDI 與地下水位時間序列的比對，建立水資源狀況的預測模型。資料來源包含 1997–2022 年 12 個氣象站的氣象資料、農業組織提供的作物資訊與地下水位紀錄。

RDI 評估指數以年尺度進行計算，整合降雨與蒸發散數據以提升對農業影響的靈敏度，結果顯示 26 年內大部分年份屬「近正常」，但仍有多次極端乾旱情形，且整體地下水位呈明顯下降趨勢。研究進一步運用時間序列模型 (ARIMA) 與廣義估計方程式 (GEE)，分別建構 RDI 與地下水位、地下水位與井水出水量之間的預測關係，並於 ITSM 與 SPSS 軟體中驗證模型的準確性，結果大多井位的 R^2 皆達 0.7 以上，具高解釋力。

地圖繪製方面，使用 ArcGIS 與 IDW/Kriging 插值方法建立 RDI 與地下水變化的空間分布圖，反映出 Fars 省北部的降雨分布與地下水條件相對較佳，南部則較為匱乏。未來 (2023–2030 年) 的預測顯示乾旱狀況趨於穩定但地下水出水量持續減少，反映區域地下水資源處於超抽危機。

在作物種植決策上，研究目標為「最大化淨收益」，建立非線性優化模型 (使用遺傳演算法於 Matlab 中實作)，同時優化「種植面積」與「灌溉減量比例 (WRF)」。研究針對五個具代表性平原 (Shiraz, Fasa, Eghlid, Kazeroon, Lar) 進行最佳化，並針對三種水價 (500、2000 與 4000 Rls/m³) 分析最適作物組合與灌溉策略。結果指出：當水價提高時，具高耗水量但經濟效益佳的作物 (如番茄、棉花、甜菜) 會被淘汰，轉為種植低耗水但仍具經濟性的作物 (如大麥、馬鈴薯)，並

提高灌溉效率。此外，作物對水分缺乏的敏感性也影響灌溉決策，較耐旱作物會配置較高 WRF 值。

綜合而言，研究證實：在乾旱頻繁與水資源受限情境下，若能結合乾旱預測、地下水動態模擬與經濟最佳化分析，即可有效配置種植面積與水資源使用，達成提升農民收益並降低地下水枯竭風險之目標。此研究亦可提供其他乾旱地區農業水資源管理的重要參考依據。

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**Providing optimal cropping patterns and water consumption
according to monitored and forecasted drought conditions**

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ABSTRACT

Drought management in the agricultural sector requires monitoring and prediction of this phenomenon, as well as providing a suitable cropping pattern. In this study, the reconnaissance drought index (RDI) was used for drought monitoring in Fars Province, Iran. The status of water resources was predicted using a model that matches the time series of the RDI and the groundwater level. The optimal cropping pattern was obtained according to the predicted available water resources using a genetic algorithm. Generally, the actual and predicted changes in groundwater levels indicate the critical conditions of groundwater resources in the study area. Groundwater resource consumption should be lowered by implementing deficit irrigation scenarios that result in keeping crops with lower sensitivity to water deficit in cropping patterns such as barley, wheat, canola, forage corn and potato. The cropping pattern optimization results suggest an increase in the area allocated to more economical crops in the northern half of Fars Province due to the better temporal distribution of annual rainfall and better water resource conditions. However, with increasing water costs, the cultivation area and the optimal water reduction fraction of these plants decreased.

KEYWORDS

cropping pattern, drought prediction, optimization, water consumption, water reduction fraction

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以簡單土壤水分監測工具提高馬拉威小農戶的產量和收入：以四種灌溉方案為例

Jonathan T. Chikankheni¹, Richard Stirzaker², Craig Strong³, Isaac R. Fandika⁴, Grivin Chipula⁵

摘要

馬拉威的灌溉面積增加，但由於農民缺乏灌溉知識，生產力仍然較低。本文介紹了一種旨在改善小農灌溉計畫水資源管理的「以人為本的學習」方法。這項工作在馬拉威開展，為布萬傑、塔達拉、南佐洛和馬塔布瓦灌溉區的農民提供了土壤水分感測器，該感測器使用顏色顯示土壤水分，使農民很容易理解土壤處於濕潤、潮濕還是乾燥狀態。在 2017 年和 2018 年灌溉季節監測了與水管理和土壤水分狀況相關的指標。然後評估產量和毛利率。結果表明，農民可以有效地識別與灌溉相關的問題，並根據工具提供的資訊採取行動。所有方案的收益率增加了 80% 以上，毛利率增加了三倍以上。根據概述的研究結果，使用土壤水分感測器可以增強農民對用水管理的了解，促使行為改變並顯著提高灌溉生產力。此外，該研究得出結論，提高農民的知識對於將小農灌溉計畫轉變為可獲利且可持續的投資至關重要。

關鍵字：變色龍土壤濕度感測器、農民學習、灌溉管理、虛擬灌溉學院

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註解

馬拉威為位於非洲東南部的內陸國家，鄰接尚比亞、莫三比克及坦尚尼亞，20%的國土被非洲的第三大湖—馬拉威湖所覆蓋，雖為具有水源之地，但由於當地開發的農地數量及耕種能力不足，造成作物生產量能低落，當地政府正視此一問題，雖於 2000 至 2011 年間開始實施優先發展灌溉的政策，短短十年間即讓小農的灌溉面積增加了四倍，即便如此，對於當地農民的生活有些許提升，但亦僅達到潛在產量的一小部分，而且僅為穀物及豆類作物，歸究其因為農民對於農事生產的灌溉技術及能力無法提升，以致農地的生產力仍舊低落。其中最主要的原因即為農民無法掌控作物生長週期，並適時灌溉，仍舊以傳統的方法進行耕作。於本研究之前，雖有學者專家研究並提供相關灌溉策略及計畫，但該些均需具有獲取天氣及土壤資訊的管道，對於基礎建設不足的馬拉威政府及接受資訊不易的農民本身而言，均為無法短時間達成的課題，是故本文作者以研究提供淺顯而易見的操作工具來協助農民，並獲得良好成效。

作者採用可適用各種土壤質的之變色龍水分感測器，對於防止農民誤用於不合適土壤的部份，具有良好的成效。其於 4 個試驗推廣灌區內，分別篩選 22 位農民，並各挑選其中兩位作為種子農民，由其教導其他農民於田間分三層土壤深度加以安裝變色龍土壤水分感測器，並協助及教導其他農民判讀、記錄感測器數據，農民可以自由選擇馬拉威當地具有指標性的小麥或大豆作物進行耕種，經由研究團隊指出，在推廣給部份農民後，農民尤其發現感測器的顏色輸出非常容易理解，讓農民可以有效地識別土壤水分狀態等相關問題並改變他們的做法，且該感測器在灌溉作物對水分不足時的最敏感範圍內具有高度反應，可有效反應作物在極端狀況下的即時水分含量，防止田間達到凋萎點後，造成作物無法存活的狀況。變色龍感測器比傳統水分張

力計具有多種優勢，特別是對於小農戶而言，一般的水分張力計需要持續維護，這對於小農而言，是一項較難以達成的任務，而其所採用之設備則無此一維護需求。於短短兩年之間，來自於 4 個不同灌區、超過 80 位農民直接參與該研究，在所有情況下，經由其設計的灌溉用水之改變，都讓作物產量大幅增加，甚至水生產率也更高了。由此可見，對於無法具有較高灌溉技術能力的農民而言，其所需要的是簡易、直覺的水分感測工具，才能協助其判斷何時開始灌溉、何時該停止，以節省用水量。臺灣在相關農業試驗所及改良場的研發及技術移轉輔助下，農民在此部份的知識能力，想必是高於該國農民不少的，尤其因為氣候所致，臺灣必須克服許多如稻熱病及植株骨幹強化以抵禦颱風經常侵略的致災問題，幸賴有農業技術單位的協助，提升及改良作物品種，並提供栽種技術方法予農民，方能讓臺灣在水果及稻米等作物的生產方面，在品質上居於翹楚之地位。對於馬拉威的農民而言，這些農耕的知識及技能，實屬難能可貴，亦無法於短時間內獲得的，是故需要如本文作者等之投入，協助農民改變生產方式，提升生活品質。

臺灣在農田水利灌溉供水工作方面，不論水源調配、輸水管理等，自早期的人工作業，已經發展自動監控系統多年，雖仍未普及至各大、中、小型分水、排水門，但在主要灌溉系統及分水工，大多已完成施設遠端監控系統並輔以自動水位監測及影像監視，近年來拜科技及資通訊的進步，讓各種水利設施的監控及監測系統，更加明顯地躍進至物聯網的境界，部份影像監視系統，更結合 AI 智慧判識現地水門操作時之人員安全。灌溉輸水渠道的各項用水管理資料在廣泛收集後，進行大數據分析，可支援提供用水管理者決策參考依據。而在用水末端的農戶，基本面的部份，除了採用可定時開啟閘門給水灌溉外，並有許多採用更進階的智慧灌溉系統，來因應人力的缺乏及水源的不足，也更為面對氣候變遷的挑戰作準備，相關經驗均可提供其他國家借鏡，

因此在面對如非洲等急需耕種及灌溉技術能力提升的國家來說，我們應可參考本文作者的出發點，檢討是否可發展成本較低、更加簡易操作且有效運作的耕種協助設備，除可達成國際援助的目標，亦可增加國際間對我國的支持。

摘要翻譯及註解：劉日順 研究員

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Simple soil water monitoring tools increase yield and income of smallholder farmers in Malawi: A case study of four irrigation schemes

Jonathan T. Chikankheni, Richard Stirzaker, Craig Strong, Isaac R. Fandika, Grivin Chipula

ABSTRACT

The area under irrigation in Malawi has increased, but productivity is still low due to farmers' lack of irrigation knowledge. This paper describes a 'peoplecentred learning' approach aimed at improving water management in smallholder irrigation schemes. The work was conducted in Malawi, where farmers at the Bwanje, Tadala, Nanzolo and Matabwa irrigation schemes were provided with soil water sensors that showed whether the soil was wet, moist or dry using colours, making it easy for farmers to understand. Indicators related to water management and soil water status were monitored during the 2017 and 2018 irrigation seasons. The yield and gross margins were then assessed. The results show that farmers can effectively identify irrigation-related problems and act on the information provided by the tools. The yield increased by more than 80%, and the gross margins increased by more than threefold across all the schemes. Based on the findings outlined, the use of soil water sensors enhances farmers' understanding of water management, prompting behavioural changes and measurable improvements in irrigation productivity. Furthermore, this study concludes that improving farmers' knowledge is essential for transforming smallholder irrigation schemes into profitable and sustainable investments.

KEYWORDS

Chameleon Soil Moisture Sensors, farmer learning, irrigation management, Virtual Irrigation Academy

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解決農業灌溉缺水問題：探索永續灌溉農業的替代水資源

Amgad Elmahdi¹

摘要

本文探討了水產業，尤其是灌溉農業面臨的挑戰，目的在提出滿足灌溉需求的解決方案，同時符合永續發展目標六(SDGS 6 確保所有人都能享有水、衛生及其永續管理)確保全球糧食安全和永續發展。本文內文架構分：增強農民能力、加強常規灌溉水源管理及利用非常規水資源等三個面向，並強調了由於降雨的多變性而探索藍色水資源的重要性。許多灌溉運作效率較低的系統，提供了提高生產力的契機。農業用水管理跨越不同層面，農民作為主要利益相關者也參與其中。除地面水外，雨水、中水、回收廢水和地下水等替代水源也可滿足灌溉需求。雨養農業(看天田)面臨降雨量不穩定的挑戰，可從雨水收集和低灌溉做法中獲益。廢水已成為一種關鍵資源，特別是在城郊地區，需要採取適當的安全措施。本文介紹了在印度維斯哈帕南(Visakhapatnam)舉行的 ICID 大會第 64 項大會議題的總報告。它提供了一個獨特的機會，讓我們集中討論替代水資源可以如何增強灌溉系統的復原能力，以及如何彌補水資源供需之間的差距。本文分為三個不同的子課題，以引導研究貢獻，並鼓勵回應者在永續灌溉農業的背景下，深入探討強化、利用和賦權等特定主題。

關鍵字：替代水資源、灌溉需求、可持續灌溉農業、水資源短缺

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註解

聯合國推估未來全球人口將不斷增加，因而加劇對糧食生產及飲用水的需求。本文係呼應第 73 屆 ICID 大會第 64 項大會議題"可為灌溉農業開發哪些替代水資源?"問題的總報告，從中歸納在滿足灌溉需求，同時符合全球糧食安全目標，特別是永續發展目標 6 (SDG6) 的相關研究與作法。本文透過三個層面探討實現可持續灌溉農業的途徑，包括現有灌溉系統的改進，應克服管理不善、地質限制、政策複雜性和氣候多變性等多種挑戰，以歸納出適應性政策、資源開發中的復原能力、綜合的 IWRM(整合性水資源管理)方法以及對不斷變化的氣候條件的適應性態度。除強調採取整體性方法的必要性，同時強調永續性的做法取決於對不斷演變的挑戰所採取的動態回應。

為解決缺水這個最重要的問題，所有研究都聚焦在提高水資源利用效率和促進農業永續發展的總體目標上。本文內容彙編跨越不同的地理區域及國家，全面探討解決灌溉與水資源管理複雜挑戰的策略，利用尖端技術和先進的創新技術，以提供可行的解決方案，促進可永續的農業發展，同時優化策略，以負責任的方式管理寶貴的水資源。探討非傳統水資源，廢水再利用及鹽水灌溉在農業上的運用，涵蓋田間實驗、灌溉水質評估及水資源再利用策略等不同主題研究成果。

灌溉技術層面，本文從灌溉噴射器設計探索開始，最終評估並加強了開創性的分流對沖流道，同時結合實驗測試與計算流體力學，以提升噴射器的效率並提供適用於類似灌溉系統的使用建議。另外，藉由加強傳統灌溉水源的管理，包括評估作物耕作技術、減緩氣候變遷和過度生產的影響等層面，避免短視的農業政策導致區域水資源失衡發展影響水土資源永續利用，例如大量抽取地下水用於農業，以及氣候變遷的影響使情況更加惡化。而利用非常規水資源，例如廢水回水再利用，即使在乾旱地區為穩定的水源但需確認其安全性，必須持續

的評估和監測維持其適用性，並且在安全及永續利用的考量下，選擇適當的廢水處理程序，同時凝聚使用共識。本文亦探討賦予農民權力以解決農業缺水問題的多層面問題，透過參與式灌溉管理(PIM)、微灌系統、透過資訊教育與溝通及發展灌溉能力創新方法等策略，以滿足日益增加的糧食生產需求，同時確保水資源的永續利用。

使用非常規水資源雖然可建立一個水資源相對穩定的環境，並實現永續的農村發展，然而再生水和鹽水雖具有環境效益，卻也面臨污染物、鹽負荷增加、生態和健康風險以及潛在的農業減產等新挑戰，因此，本文也提醒透過持續研究、創新和適應性策略，例如鹽水灌溉對土壤健康的影響，以及採取創新的排水措施來緩解土壤鹽化問題，減輕新水源或再生水源帶來的負面環境效益。農業的非傳統水資源(廢水再利用及鹽水)的灌溉利用，在臺灣尚未推廣使用，再生水僅限於景觀澆灌及消防用水，不能接觸身體。現階段因再生水利用條例及自來水法等法規限制，規範高耗水產業使用生活污水處理後之再生水，以穩定國內經濟發展並減少供水的壓力。面對缺水問題，亟需增強農民的應變及調適能力，青年參與及公私合作或許為增強農民能力相對可行的方法與模式。隨著全球人口持續上升，為了農業的復原力和永續性，賦予農民能力將日漸重要，由人的角度出發，思考採用適應性策略、利用技術和創新，以及促進利害關係人之間的合作為永續農業發展、優化水資源利用並減輕缺水所帶來的挑戰，是確保未來所有人都能享有水資源安全及糧食安全的關鍵。

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Addressing water scarcity in agricultural irrigation: By exploring alternative water resources for sustainable irrigated agriculture

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ABSTRACT

This review paper addresses challenges in the water sector, particularly in irrigated agriculture, aiming to propose solutions for meeting irrigation demands while promoting global food security and sustainable development, notably SDG 6. Structured around three facets: empowering farmers, strengthening conventional sources of irrigation water and harnessing non-conventional water resources, it emphasizes the significance of exploring blue water resources due to precipitation variability. Many irrigation systems operate below efficiency, offering productivity enhancement opportunities. Water management in agriculture spans various levels, involving farmers as key stakeholders. In addition to surface water, alternative sources like rainwater, grey water, recycled wastewater and groundwater can meet irrigation needs. Rainfed agriculture, facing challenges from erratic rainfall, can benefit from rainwater harvesting and under-irrigation practices. Wastewater emerges as a pivotal resource, particularly in peri-urban areas, necessitating appropriate safety measures. This paper presents the General Report of Congress Question 64 of the ICID Congress in Visakhapatnam. It provides a unique opportunity to focus on how alternative water resources might enhance the resilience of irrigation systems and bridge the gap between water supply and demand. The subdivision of the paper into three distinct subtopics guides research contributions, encouraging responses that delve into the specific themes of reinforcing, harnessing and empowering, all within the context of sustainable irrigated agriculture.

KEYWORDS

alternative water resources, irrigation demand, sustainable irrigated agriculture, water scarcity

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毛細吸水芯灌溉提升綠豆種子產量與水分利用效率

Mansoor Rezaei, Hassan Heidari¹

摘要

乾旱是全球作物生產的重要威脅，尋求新型灌溉方法可達到節水的目標。本研究於伊朗克爾曼沙阿的溫帶半乾旱地區，評估吸水芯灌溉 (wick irrigation) 對綠豆種子產量、水分利用效率 (WUE) 及形態生理特性的影響。灌溉處理包含：吸水芯灌溉、灌水量與吸水芯灌溉等量的面灌 (surface irrigation)，以及灌水量為吸水芯灌溉兩倍的面灌。結果顯示，與等量面灌相比，吸水芯灌溉顯著提高單株種子重 164%、百粒重 14%、每莢粒數 28%、單株莢數 80%，並使種子產量與生物量分別增加 164%與 128%。種子 WUE 與生物量 WUE 亦分別提升 164%與 128%，淨收入也增加 300%。此外，吸水芯灌溉亦將植株高度、節間長、單株葉片數、節數、分枝數、葉長及葉寬分別提升 60%、59%、65%、91%、91%、52%與 52%。綜上所述，吸水芯灌溉可在節水條件下有效提升綠豆產量與淨收益，為乾旱及水資源緊張地區提供可行的灌溉替代方案。

關鍵字：毛細運動；減量灌溉；乾旱；面灌；節水

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註解

當綠豆生長時受到水分短缺的脅迫，其產量會減少。為減緩乾旱造成的問題，引入新型灌溉技術至關重要。傳統的灌溉方法，如漫灌或溝灌，往往導致大量水分的浪費，包括深層滲漏、地表逕流以及蒸發損失，進而降低了水分利用效率（Water Use Efficiency, WUE）。相較於傳統灌溉，地下灌溉系統更省時、省水，且省經費。吸水芯灌溉（Wick Irrigation），是一種近年來重新受到關注的地下灌溉技術。其基本原理是利用毛細管作用（capillary action），通過吸水芯材料（wick material）將儲水器中的水分緩慢且持續地輸送至植物根系的土壤中，避免了過量灌溉或水分脅迫的發生，適用於缺水地區。

本項研究的實驗地點位在伊朗的拉其大學，共進行兩年的田間試驗。研究中設置了三種處理：吸水芯灌溉（WI）、灌水量與吸水芯灌溉等量的地面灌溉（surface irrigation）（S1），以及灌水量為吸水芯灌溉兩倍的地面灌溉（S2），並對每種處理實施三重複試驗。在吸水芯灌溉系統的設計環節，研究團隊以三個有刻度的 30 公升儲水桶為水源，透過等長軟管與棉質吸水芯連接，每桶分四路輸水至 2 公尺的種植行。吸水芯前端漂浮於桶中吸水，水分藉由毛細作用流向行內四個灌點，間距 0.5 公尺，確保整行均勻濕潤。側向出口長度控制小於 10 公分，以防近端過吸；所有分支等長設計則避免末端缺水，解決傳統單一出口近遠端供水不均的問題。

本實驗旨在量化比較吸水芯灌溉與傳統灌溉方式在綠豆種植中對種子產量和水分利用效率的具體影響。試驗的測量指標包含：單株莢數、每莢粒數、百粒重、單株種子重、收穫指數（HI）、地上部生物量、種子產量、生物量產量、種子與生物量 WUE、株高、節間長、分枝數、葉片數、節數、葉長、葉寬，以及葉片相對含水量（RWC）、氣孔導度與葉面溫度。所有數據以變異數分析（ANOVA）檢定處理

效應，並以 LSD 5 % 水準比較平均值。

產量結果顯示，WI 在所有主要構成要素上均顯著優於等水量面灌 S1。與 S1 相比，WI 將單株種子重由 3.26 g 提升至 8.59 g (+164%)、百粒重由 6.82 g 增至 7.79 g (+14%)、每莢粒數由 8.3 增至 10.6 (+28%)、單株莢數由 10.9 增至 19.6 (+80%)。在田間尺度，WI 的種子產量達 1533 kg ha⁻¹，較 S1 的 580 kg ha⁻¹提高 164%，亦顯著高於用水翻倍的 S2 (1048 kg ha⁻¹)。地上部生物量亦以 WI 最高 (3410 kg ha⁻¹)，較 S1 增加 128%。

WUE 分析進一步驗證 WI 的節水優勢。WI 的種子 WUE 為 0.87 kg m⁻³、生物量 WUE 為 1.93 kg m⁻³，較 S1 (0.31 與 0.84 kg m⁻³) 分別提升 164% 與 128%；而 S2 因用水倍增導致 WUE 反下降至 0.30 與 0.80 kg m⁻³，顯示單純增加灌溉量並不能換取更高的水分效率。

形態觀測結果同樣呈現 WI 的正向效應：植株高度由 26.9 cm 增至 43.0 cm (+60%)、節間長由 2.8 cm 增至 4.5 cm (+59%)、葉片數由 12.3 增至 20.3 (+65%)、節數由 7.9 增至 15.1 (+91%)、分枝數由 3.4 增至 6.5 (+91%)，葉長與葉寬分別增加約 52%。然而葉片 RWC (約 82–85%)、氣孔導度與葉溫在三處理間差異不顯著，顯示 WI 提供的連續微量水分並未造成葉面過濕或氣孔調控失常。

本研究指出，WI 之所以能在不增水的情況下顯著增產，關鍵在於毛細導水維持了根系周圍穩定且接近田間持水量的含水環境，降低了地表蒸發與深層滲漏損失，同時避免了傳統間歇式灌溉易引起的土壤濕乾波動。此種「持續小流量」補水模式，特別在開花至灌漿期(需水最敏感期)有效減輕水分逆境，使胚乳灌漿順利完成，進而同步提升百粒重、粒數與莢數等產量構成因子。

經濟分析顯示，在成本相同的前提下，WI 因吸水芯材料與安裝費用，變動成本較 S1 高，但其種子產量更高，最終淨收益遠高於面灌的 S1 與 S2。其投入產出比亦以 WI 最高，顯示其在農戶經濟面具

高度可行性。

總結而言，吸水芯灌溉能在不增加灌水量甚至減少用水的情況下，顯著提升綠豆產量、形態生長、水分利用效率與經濟效益，其核心優勢包括連續穩態供水減少非生產性耗水、抑制雜草及結殼、以及低能耗與架設簡易等特點。此研究認為，WI 可作為乾旱及半乾旱地區綠豆生產的有效替代灌溉策略，並建議後續在更大區域與不同作物上進行長期評估，以全面驗證其水分動態與產量效益。然而，吸水芯灌溉的推廣應用也面臨一些挑戰，例如：吸水芯材料的選擇（需具有良好的吸水性和耐用性，且成本低廉）、儲水器的設計與維護、系統在大面積應用時的安裝佈局與成本效益分析、以及在不同土壤類型和氣候條件下的適應性調整等。未來應針對擴大規模與商業化進行設計與研究。

對照台灣之農業發展，雖然灌溉系統相對完善，但在特定季節性缺水和部分偏遠地區，要避免乾旱，水資源的有效利用仍是重要課題。本研究揭示的吸水芯灌溉在綠豆上的成功應用，對於台灣種植豆類作物或其他對水管理敏感的經濟作物，提供了一個值得參考的節水灌溉模式。

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Wick irrigation improves seed yield and water use efficiency in mung bean

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ABSTRACT

Drought is a serious threat to crop growth, and finding new irrigation methods can save water. This study investigated water use efficiency and seed yield in mung bean under wick irrigation. Irrigation treatments comprised wick irrigation, surface irrigation with water equivalent to wick irrigation, and surface irrigation with double the water use of wick irrigation. Wick irrigation increased seed weight per plant, 100-seed weight, seed number per pod, pod number per plant, seed yield, biological yield, water use efficiency of seed, and water use efficiency of biomass by 164%, 14%, 28%, 80%, 164%, 128%, 164%, and 128%, respectively, compared with surface irrigation using an equivalent water volume. Plant height, internode length, leaf number, node number, branch number, leaf length, and leaf width were also enhanced. Wick irrigation can thus save water while improving seed yield and net income.

KEYWORDS

capillary movement, deficit irrigation, drought, surface irrigation, water-saving

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運用作物水分壓力指數 (CWSI) 評估地中海型氣候條件下 覆盆子作物之水分利用效率

Catherine Vargas-Castro, Cristian Mattar, Oscar Seguel & Ítalo Moletto-Lobos

摘要

地中海型氣候區的中部智利正面臨水資源日益減少的風險，因此需發展永續的灌溉管理策略。本研究透過遙測和土壤感測資料，使用作物水分壓力指數 (crop water stress index, CWSI) 和 SSEBop 模式估算實際蒸發散 (ETa)，評估兩個覆盆子田區的水分利用效率 (water use efficiency, WUE)。研究結果顯示：SSEBop 模式估算 ETa 的準確性良好 ($R^2=0.92$, $RMSE=0.97$ mm/day)，CWSI 能有效偵測灌溉後的高壓力時段。兩試區灌溉水量差異顯著 (17,097 與 3,760 m^3/ha)，導致 WUE 值分別為 0.79 與 3.64 kg/m^3 。研究建議非關鍵生育期僅補足 85% ETa 以提升灌溉效率，以及突顯 CWSI 在乾旱風險下對灌溉優化的重要應用潛力。

關鍵字：CWSI、乾旱壓力、蒸發散、SSEBop、水分利用效率 (WUE)

註解

智利中部為地中海型氣候區，是該國主要農業生產區，但氣候變遷導致水資源供給不穩。特別是在覆盆子（raspberry）等高經濟價值作物中，合理灌溉至關重要。過去多以經驗或定值作為灌溉依據，導致效率低。本研究整合遙測資料、氣象監測與作物水分壓力評估指數（CWSI），發展適用於小型農場的灌溉監測方法，並透過兩個田區（A、B）的比較，探討最佳灌溉管理方式。試驗地位於智利中部 O'Higgins 地區，兩個覆盆子園區（A 區 3 公頃、B 區 1.5 公頃）使用溝渠灌溉。從 2016 至 2019 年間進行氣象與遙測資料的同步收集。遙測數據來自 Landsat 7 與 8 共 45 景影像，並透過 SSEBop 模式計算 ETa。地面監測則使用 CCS 站點的感測器收集土壤含水量、氣溫、地表溫度、輻射等變數。

本研究整合遙感技術與現地監測資料，建立一套可應用於地中海型氣候條件下的果樹水分監控與灌溉優化方法，主要由三個技術核心組成：實際蒸發散估算（ETa）、作物水分壓力評估（CWSI），以及水分利用效率（WUE）計算。

1. 實際蒸發散估算（SSEBop 模式）

研究使用了 SSEBop（Operational Simplified Surface Energy Balance）模式來估算覆盆子作物的日蒸發散（ETa）。此模式為地表能量平衡的簡化版本，能在缺乏高密度氣象資料的區域，利用 Landsat 衛星影像與基本氣象數據，如風速、氣溫與輻射等變數，進行較為精準的 ET 估算。

2. 作物水分壓力指數（CWSI）

為進一步辨識作物在生育期間的水分壓力情形，本研究運用了作物水分壓力指數（CWSI）。該指數透過遙測影像中地表

溫度與空氣溫度的差異，以及植被指數（NDVI）進行水分壓力的量化評估。研究根據不同 NDVI 門檻值，分別篩選出代表充分灌溉的冷像素與水分壓力區域的熱像素，進一步估算 CWSI 的空間分布與時序變化。

3. 水分利用效率（WUE）

WUE 的計算整合了兩項變數：作物實際產量與所施用的灌溉水量。在本研究中，產量資料來自農場實際收穫記錄，涵蓋兩次主要採收（主梢與側芽）；而灌溉水量則由水流流速、時間與灌溉頻率計算而得。此指標可用來直接比較不同灌溉管理策略下的水資源使用成效，為農業經營提供明確的效率指標。

本研究透過三年時序資料分析，SSEBop 模式在估算 ETa 方面展現出高準確度，其模擬結果與實地監測之蒸發散值呈高度線性關係，誤差範圍控制在 ± 1 mm/day 內。地表溫度的估算亦與實測吻合，證明模式於不同季節與作物生長階段均具適用性。

在灌溉行為上，兩區農場表現差異顯著。A 區年灌溉總水量高達 17,097 m³/ha，屬過度灌溉，而 B 區僅施用 3,760 m³/ha。儘管如此，兩區最終年產量差距不大（約 16 噸/公頃），導致 WUE 在 B 區顯著高於 A 區（3.64 vs 0.79 kg/m³），凸顯節水策略在維持產量下仍可提升效率。

CWSI 監測顯示，春季初灌溉頻率較低時，指數值迅速上升至 0.8，表示作物承受顯著水分壓力；而在夏季高頻灌溉階段，CWSI 值下降至 0.2–0.4 之間，說明作物處於理想水分狀態。空間圖層進一步揭示，不同農戶間的灌溉管理差異直接反映在作物壓力程度與 ETa 的空間變異上。

本研究指出，農場 A 區灌溉明顯超出實際蒸發散需求，導致水資源浪費且未帶來產量效益。此現象在許多中小型農場普遍存在，主因

包括依賴傳統經驗判斷、缺乏感測資料，以及灌溉系統難以精準控制。相較之下，B 區雖用水較少，但藉由適當灌溉頻率與土壤滲透力的應用，使得作物水分壓力控制得宜，產量維持穩定，顯示精準灌溉管理之效益。

在臺灣面臨氣候變遷、水資源不穩定與農業用水競爭日益加劇的情勢下，本研究提出的整合型灌溉監測方法，對於國內農業水資源管理具有高度參考價值。臺灣中南部許多果樹與高經濟作物栽培區域，例如柑橘、芒果、番石榴等，多採用傳統溝渠灌溉或定期人工灌溉方式，然而灌溉量與頻率往往依據農民經驗調整，缺乏即時監測工具，導致灌溉過量、土壤滲漏或水分壓力反應不及的問題普遍存在。若能導入本研究中所示的 SSEBop 模式進行大範圍蒸發散估算，搭配遙測影像與少量氣象資料，即可有效掌握區域級別的作物實際需水情形，建構出符合生長時序的灌溉建議圖層，提供灌區管理單位與農戶參考。

此外，作物水分壓力指數（CWSI）的應用對於臺灣小型農戶而言尤其具實用潛力。相較於昂貴的感測器布建與維運，CWSI 能以公開遙測資料快速辨識作物水分壓力程度，作為調整灌溉時機與頻率的即時參考。透過 NDVI 與熱影像的組合應用，農政單位可建立分區水分壓力預警系統，提升應變能力，尤其在春末初夏的關鍵灌溉期，對減少乾旱損失具有重要意義。

更進一步地，水分利用效率（WUE）的量化概念亦可納入臺灣灌溉制度的管理與獎補助機制，作為推動精準農業與節水型灌溉系統的重要指標。透過評估單位灌溉水所產出的農產品價值，不僅能促進水資源公平分配，也能驅動農戶採用更具效率的滴灌或智慧灌溉技術，進一步實現高產低耗的永續農業目標。

摘要翻譯及註解：江莉琦 副教授

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Using a crop water stress index to determine water use efficiency in a raspberry crop in the Mediterranean Central Chile

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ABSTRACT

Water availability is projected to decrease in Mediterranean Central Chile, necessitating sustainable production strategies based on improved irrigation management. This study focuses on estimating water use efficiency (WUE) in raspberry crops at two validation sites using remote sensing and soil irrigation data. By employing the crop water stress index (CWSI), we demonstrate the potential of this tool in enhancing irrigation management and establishing sustainable production practices. The results demonstrate the successful estimation of actual evapotranspiration (ET_a) using the Operational Simplified Surface Energy Balance (SSEBop) model (coefficient of determination [R^2] = 0.92; root mean square error [RMSE] = 0.97 mm day⁻¹), while the CWSI indicated high stress levels after 5 days of irrigation. Moreover, validation at two sites reveals significant differences in applied irrigation, with sites A and B receiving 17,097 and 3760 m³ ha⁻¹, respectively, while the average water demand is close to 5300 m³ ha⁻¹. These variations result in discrepancies in WUE, with values of 0.79 and 3.64 kg m⁻³. By integrating remote sensing indices and soil data, this study proposes that maintaining an 85% ET_a rate during noncritical periods can enhance WUE. This work demonstrates the potential use of a water stress index to monitor crops in the Chilean central zone for efficient water resource use under future scarcity scenarios.

KEYWORDS

CWSI, drought stress, evapotranspiration, SSEBop, water use efficiency

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農業灌溉排水系統之生態服務：全球願景

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摘要

農業灌溉用水供給全球 40% 的糧食農作物，但是經常伴隨對環境的負面影響。深深的體認到農業灌溉用水，除了糧食生產功能外，亦提供生態服務及緩和氣候變遷影響。現今世界上一些應用案例，包括在日本的水田應用於防洪；在南非與臺灣案例，其用於強化改善水質及水資源再利用；在衣索比亞與日本，用於微型或中尺度氣候調適；在法國應用於最大化碳封存或最小化碳逸散；在土耳其應用在地下水位管理，減少灌溉用水需求等。灌溉基礎設施方面，例如梯田景觀(日本)、大型的壩或圳路(澳洲)，帶來額外的生態旅遊效益。這些研究案例分析進而找到機會，並藉由使用國際生態服務系統進行交互比較。建議發展一個規劃框架，尋找最佳化生態服務系統，對於灌溉用水來源及管理提供激勵措施。

關鍵字：控制排水、生態旅遊、蒸發冷卻、劣水質、地下灌溉法、水收集

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註解

農業灌溉用水系統供給全球 40% 的糧食農作物，佔陸地的 20%，雨水澆灌系統佔 60% 的糧食作物，佔陸地的 80%。體認到農業灌溉用水，除了糧食生產功能外，亦提供生態服務及緩和氣候變遷影響。灌溉與排水最重要的標的是糧食生產的生態服務。同時灌溉與排水系統亦推進鄉村經濟發展、支援服務（土壤健康）、調適服務（洪災）、文化服務（休閒、身心等效益）。本文由 ICID 的環境工作小組(WG-ENV)提出現今世界各國案例（參閱圖 1），闡述灌溉排水系統、控制排水及地下灌溉法如何提供生態服務，同時降低負面環境衝擊。生態服務具提高生產力及永續性之效益。生態服務的貨幣價值評估亦是本文重點之一，本文提出之案例研究，針對爭議的議題探討及利害關係人在當中扮演之角色。

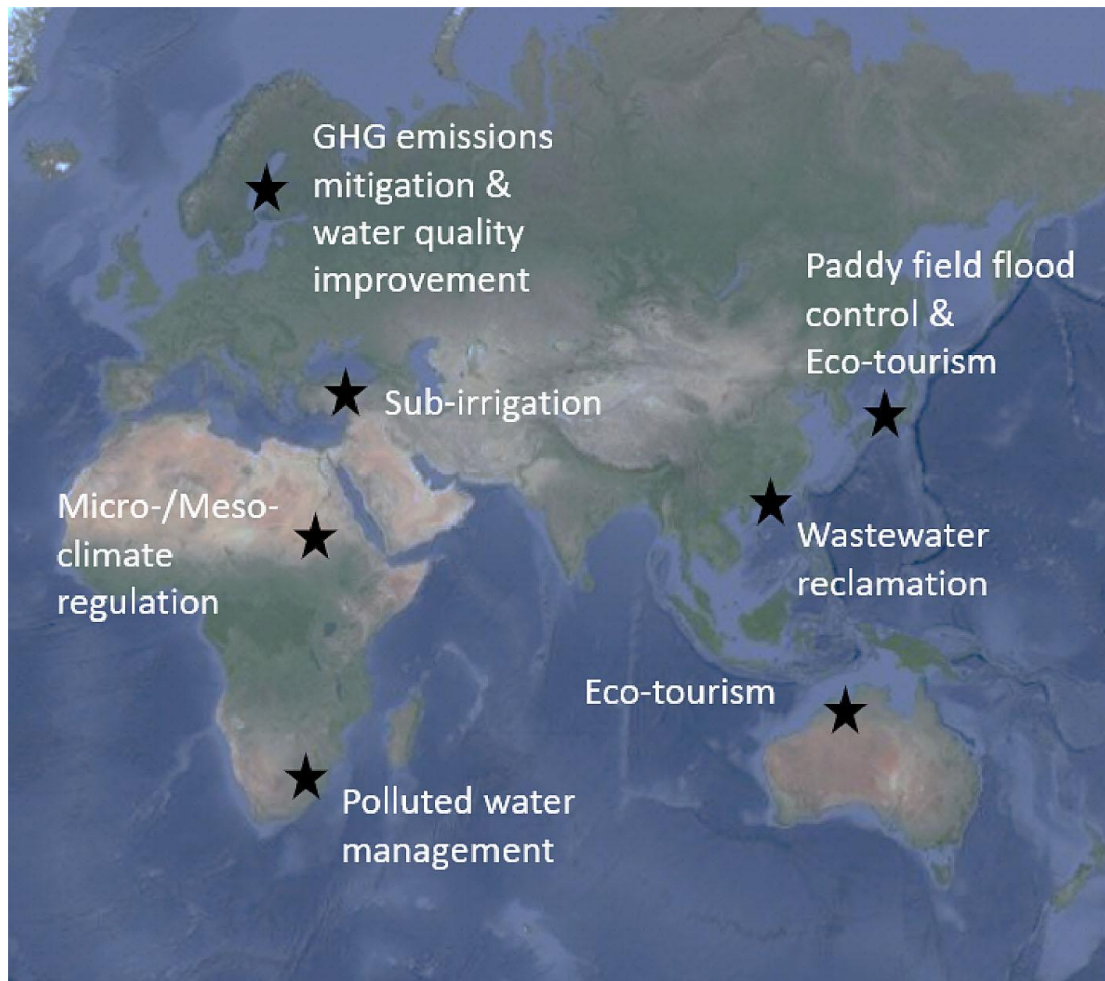


圖 1 生態服務案例地點

生態服務的貨幣價值評估及實行常是一個挑戰，本文案例彙整潛在數值關於支付生態服務費用，補貼或補償環境潛在支出費用等。以優勢（Strengths）、弱勢（Weaknesses）、機會（Opportunities）、威脅（Threats）SWOT 分析優缺點，挖掘其效益、衝擊及執行風險等。

日本的水田應用於防洪案例，利用設置於水田的暴雨逕流控制出口，控制入流並以水田蓄存部分降雨逕流，其可降低河川洪峰、增加流域蓄水量、增加地下水補注等優點。自 1980 年代，大量現地研究在日本及亞州實行，近年進行水田蓄水量測及洪水調適功能測試，水田出口裝置水位調節設施，降低及延遲河川下游洪峰，Yoshikawa 等人，應用動力波模式進行水田逕流分析。Hatcho 等人，以 HEC-HMS 模擬水田設置逕流調節設施後集水區逕流量分析。在衣索比亞與日本，

水田應用於微型或中尺度氣候調適，藉由蒸發散的熱交換，達到調適都市周邊溫度效益。衣索比亞的伊娜柏德河流域(Enabered river basin)進行水田雨水收集試驗，在夏天偵測達 1.74 °C 降溫效益。

農業灌溉排水系統使用控制排水及地下灌溉法，在芬蘭設置控制排水及地下灌溉設施，研究指出除了水量控制，在水質具改善效益，尤其降低非點源營養鹽負荷量的釋出，改善流域的水質。另外，針對溫室氣體 (greenhouse gas, GHG) 提供 12% 的逸散控制效益，在法國應用於最大化碳封存或最小化碳逸散，在泥炭含有機物質的灌排系統中進行有氧生物降解，其逸散的二氧化碳及一氧化氮是較高的，控制地下水位接近於土壤表層，可降低溫室氣體釋出，在土耳其應用在地下水位管理，減少灌溉用水需求等。

梯田景觀(日本)、大型的壩或圳路(澳洲)，帶來額外的生態旅遊效益。生態旅遊在日本稻米文化扮演社會效益的角色，以日本稻米種植的發展歷史而言，已經根深蒂固與水及其社區相互連結。特別是梯田視為日本鄉村及里山 (Satoyama) 文化的基本要素。近年農業勞力減少及老化、農地廢棄等問題，導致在丘陵及山區地區的農村社區經濟停滯。因此，倡議農業旅遊、生態旅遊、綠色旅遊等方式導入農村社區。物主系統 (owner system) 是一種讓都市或非農民參與農作的系統，參與的人只要支付年費，就可以經驗擁有參與及經營管理梯田，參與計畫的人可以從事整田、插秧、鋤草、收割等稻米生產完整的過程及收到自己種植的稻米產品。日本目前已有 11 個遺址被 ICID 選為世界灌溉工程遺產 (World Heritage Irrigation Structures, WHIS)，其中 3 個為水田，藉以吸引更多觀光人潮。在澳洲西邊灌溉基礎設置，吸引大量觀光人潮，其中 Lake Kununurra 是國際濕地拉姆薩 (Ramsar) 公約所列的濕地，藉以增加生態旅遊成效。

因應氣候變遷及更頻繁極端氣候事件，需增加投資在維護灌溉排水基本設施，強化面對氣候變遷的韌性。本研究蒐集各種不同的案例，

其採用的各種措施，藉以因應極端的情況，透過 SWOT 分析，採取可行措施，並強化生態服務策略。這些研究案例分析進而找到機會，並藉由使用國際生態服務系統進行交互比較。建議發展一個規劃框架，尋找最佳化生態服務系統，對於灌溉用水來源及管理提供激勵措施。正面及負面的評估是重要的，評估既有灌溉排水設施，規劃未來設施，都必須將生態服務視為水永續管理的一項重點。

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Ecosystem services of irrigated and controlled drainage agricultural systems: A contemporary global perspective

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ABSTRACT

Irrigated agriculture provides 40% of the world's crop-based foods but often with a negative impact on the environment. It is important to recognize that in addition to providing food and fibre, irrigation and controlled drainage systems can be optimized to provide additional ecosystem services and mitigate climate change by using resources in a more efficient way. Contemporary case studies were identified from around the world, including flood control by paddy fields in Japan, water quality enhancement and wastewater reuse in South Africa and Taiwan, micro-/meso-climate regulation in Ethiopia and Japan, controlled drainage and sub-irrigation to maximize carbon sequestration and minimize leaching in Finland, and groundwater table management to reduce irrigation water and pumping requirements in Turkey. Irrigation infrastructure, such as rice paddy terraced landscapes (Japan) and large dams and canals (Australia), have also achieved notable additional ecotourism job creation. Case studies were analyzed in terms of funding opportunities and compared using the Common International Classification of Ecosystem Services system. It is recommended that planning frameworks be developed that seek to optimize ecosystem services such as the ones discussed above. Policy should be updated to recognize these services and provide incentives to irrigators and water management entities accordingly.

KEYWORDS

controlled drainage, ecotourism, evaporative cooling, poor quality water, sub-irrigation, water harvesting

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以水田作為減洪措施之潛力

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摘要

近期氣候變遷導致全球嚴重的天災事件頻繁發生，為了適應這些事件進而促進相關調適措施的需求方法醞育而生。利用自然方式及措施（或稱為“綠色基礎設施”）的調適措施、防災及減災機制，已廣泛地被許多國家所認可與接受。自2015年以來，日本也促進了相關基於利用生態方式的減少災害及風險方法。其中，‘Tambo Dam’（TD），為本文作者曾參與利用水田區域進行的減洪措施之計畫，已成為在日本相當具潛力廣泛採用的綠色基礎設施之一。本研究概述了‘Tambo Dam’的逕流控制機制，並展示其在流域尺度方面有效減少洪水災害的成果，也討論其成功且可持續的兩個關鍵因素：即適當的逕流控制設備設計與精心制定的管理計畫，以激發農民的支持與參與。結果顯示，Tambo Dam 措施的實施已成為農業資源管理的重要策略。同時，利用這種管理措施亦可保留水田的功能。這種做法不僅有利於減洪，而且確保在緊急情況下可迅速恢復水稻的種植。此外，建立於見附市的 Tambo Dam 系統，是透過「多功能行動直接支付方式」進行維護與營運管理，以確保 Tambo Dam 長期執行之可行性。

關鍵字：管理計畫、生態減災、減輕洪澇災害、綠色基礎設施、逕流控制設備、水田埧。

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註解

「Tambo」即日语「田んぼ」(水田),「Tambo Dam (TD)」並非傳統上的水堤,而是在日本一種基於農業生態系統的創新型防洪策略,亦即利用水田進行防洪設施或管理方法,其核心目的是在特定條件下充當臨時蓄水池的功能,通過調節水田的水位來減緩暴雨期間的洪水致災壓力。其原理為在暴雨期間,農民通過暫時關閉水田的排水口,將雨水蓄積在水田中,減少直接排入河流的水量,進而減緩下游洪水致災風險。

本研究為日本新潟大學科學技術研究所與寒帶區土木工程研究所 Natsuki Yoshikawa 等人,在日本不同地區進行 TD 措施之研究,截至 2023 年止農林水產省(Ministry of Agriculture, Forestry, and Fisheries, MAFF)已於全國 37 個縣的超過 87,000 公頃水田實施或正在實施採用 TD 生態減災之研究計畫。基於採取 TD 措施仍屬於地方倡議並獎勵農民參與利用稻田作為一種綠色基礎設施(Green infrastructure, GI),過去在日本實施過程中亦面臨農民參與度及意願下降等問題,茲將本文所提出的關鍵問題與相關建議歸納如下:

1. 本研究農民透過在稻田中安裝排水箱及逕流控制設備,例如孔口或溢流堰,減少了連接稻田及排水溝的排水量,有效地將水田變成 TD,減緩在強降雨高峰期間整個流域中從稻田流出的逕流量,進而緩解河川尖峰流量,減少下游洪水災害。
2. 為了適合不同區域之農田排水系統,由新潟大學研究團隊指導私人公司開發一系列適合不同排水口形狀之各式逕流控制設備,成本範圍一般在每 1,000 平方公尺約 1 至 30 美元間,其價格取決於所採用的材料及設備類型。
3. 在「低窪農業區」之研究方面:於新潟平原進行的評估結果顯示在每個流域內之所有稻田均實施 TD 下,可以減少淹水面積

約 30 至 50%，在沒有逕流控制設備的情況下，逕流量隨降雨強度波動較大；然而，當安裝逕流控制設備時，逕流量幾乎不受降雨量的影響（即使降雨量增加，逕流量峰值保持不變）。因此，降雨強度越大，TD 有效地減少峰值逕流量則更顯著。在這種情況下，TD 實施後，對於 150 毫米/24 小時及 300 毫米/24 小時降雨事件，分別減少了 65%及 83%之峰值逕流量。

4. 在「流域防洪」之研究方面：由宇都宮市 2019 年 10 月海貝思颱風之案例研究顯示，實施 TD 減少該流域所有稻田之峰值逕流量約 9%，有效降低河川水位 25 毫米，進而減少堤防溢流發生、溢流量持續時間，顯著減少溢流深度約 50%，使得宇都宮地區淹水面積減少 40%。
5. 與傳統的防洪措施相比，農民的參與及建立共識對於推動 TD 的實施成功與否至關重要。因為這些措施的有效性取決於必須透過農民持續參與及長期維護管理。根據本文作者的實地經驗，即使是同意實施 TD 安裝設備的農民在參與數年後亦可能會出現參與度下降之趨勢，特別是在雨季，為了改善自身農田的排水，有更多的農民選擇在這個關鍵時期移除他們的設備。為了解決這個問題，研究中必須透過重新設計調整管理水深的高度與逕流控制設施。當溢流排放量超過孔口的流出容量，並超過目標水深時，多餘的水流可通過深度控制板進入排水箱。此系統僅在強降雨期間自主啟動，避免及減輕對農民日常排水管理的干擾與負擔。
6. 此外，安裝逕流控制設備對水稻生產所造成的負面的影響（例如會降低水稻產量或稻米品質）亦將使得上游沒有直接受益的農民缺乏參與 TD 之意願與動機。因此，需要更多公共補償政策方式提供參與農民的獎勵，MAFF 正式將一項“多功能行

動直接支付方式”納入修訂於 TD 實施計畫中，以獲得參與 TD 稻田之相關補助金利益。

7. 此外，存在上、下游農民之間傳統水資源管理的歷史衝突分歧，在於圍繞 TD 實施的負擔-收益原則上，這種錯位是阻礙 TD 實施過程中共識建立與破壞後續努力之可持續性。因此，實施 TD 成功而聞名的見附市，自 2010 年以來制定了一套獨特的「區域協議」方案，見附市的成功可以歸因於其透過實施激勵農民所精心設計之行政方案是一個值得借鏡的成功案例。

台灣近年受氣候變遷與極端氣候加劇影響，旱澇交替頻仍發生，將同時面臨乾旱缺水風險及強降雨農田致災之嚴峻農業水資源挑戰。再者，台灣目前亦如同鄰國日本所面臨之糧食自給比例下降，飲食消費模式的轉變、稻米糧食政策，以及農民人口老化進一步加劇造成稻田種植面積逐漸減少，導致稻田的荒廢與破壞，損害農業利益等各種不利農業發展之嚴峻挑戰。本文提出實施 TD 之倡議已成為管理農業資源之重要策略，透過農田成為 TD 進行平時維護管理以維持並保留基本耕地，避免因稻米供應過剩導致耕地面積減少。此方法不僅有助於防洪減災，還能確保在緊急情況下仍可迅速恢復水稻種植與生產。因此，TD 的實施不僅可以減輕洪水災害，亦可作為制定加強糧食安全與維護國土永續性等相關政策推動策略之參考應用。

摘要翻譯及註解：王鵬瑞 博士

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Potential of Tambo Dam implementation as a flood control measure

Natsuki Yoshikawa, Naoko Koshiyama

ABSTRACT

Recent climate change has resulted in severe and frequent natural disasters globally, prompting the need for adaptation to these events. As an adaptation measure, disaster prevention and mitigation using natural processes and mechanisms (or ‘green infrastructure’) have become widely recognized in many countries. Ecosystem-based disaster risk reduction has been promoted in Japan since 2015. The ‘Tambo Dam’, a flood mitigation project using paddy fields in which the authors have participated, has the potential to become one of the most extensive forms of green infrastructure in Japan. This study outlines the runoff control mechanisms of Tambo Dams, demonstrates their effectiveness in reducing flood damage at the watershed scale, and discusses two key factors for successful sustainable efforts: the design of appropriate runoff control equipment and administrative schemes that support incentives for the efforts of farmers. The results indicated that Tambo Dam implementation represented a crucial strategy for managing agricultural resources. The functionality of paddy fields could be preserved by managing them as Tambo Dams. This approach not only contributes to flood control but also ensures a swift return to rice cultivation during emergencies. Moreover, establishing a system akin to the Tambo Dam initiative of Mitsuke City, supported by the ‘Direct Payment Scheme for Multifunctional Activities’ for maintenance and management, could ensure the feasibility of Tambo Dam implementation.

KEYWORDS

administrative scheme, eco-DRR, flood damage mitigation, green infrastructure, runoff control equipment, Tambo Dam.

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摩洛哥農場運用滯洪池補注地下含水層及灌溉用水之聯合 運用研究

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摘要

乾旱地區，藉由滯洪池收集雨水，其水量可提供額外的地表水使用及補充地下水層水量，進而能夠緩解灌溉用水導致地下水損耗。本計畫設計一個現地試驗，量化位於摩洛哥瓦迪(Wadi Satt)農場的地下水通量估算。當地的地下水來自於摩洛哥東南方的安迪阿提斯山脈，試驗場使用自動化氣壓計水位計，監測容量 6500 m³ 滯洪池的水位，於 2021-2023 的計畫期間蒐集 6 場洪水事件進行分析。利用滯洪池水量平衡分析，指出大部分(56%收集的洪水)的蓄留水是被抽取為灌溉用水，超過 40%水量是以入滲率 90 mm day⁻¹ 入滲地下水及其他損失如蒸發等。池子的水位系統模擬分析入滲導致之地下水影響半徑少於 360 m。池子的灌溉圖觀察到地下水補注情況，經由持續抽取數週後，由兩個相近的洪水事件，看出地表水是進行補注至地下含水層。建議未來滯洪池進一步擴大使用在集水區尺度，應分析對於下游水資源的負面衝擊。

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關鍵字：分析模式、滯洪池、地下水補注、摩洛哥綠洲、引洪灌溉、
水收支平衡分析

註解

在乾旱地區，農業用水常依賴傳統灌溉及雨水收集設施進行供水，本文敘述在摩洛哥農場使用大量地窖、蓄水池等古代的蓄水設施。1980年代，摩洛哥農業灌溉的蒐集及永續灌溉實務有長足進展，灌溉方式逐步依賴抽用地下水。隨著用水的成長，一些農場構築土堤農塘，收集洪水提供農業灌溉，並補注地下水。以模式評估地下水入滲效率，量化地下水補注量。使用農塘收集洪水，達到雙重目的，包括補注地下水及成為灌溉用水來源。水資源運用角度，為達最大補注量，將降低灌溉用水量，在本計畫藉由水理模式及現場試驗，計算這兩個交互消長的目的函數式，優化其最大整體效益。圖1為本計畫之研究區域及地下水監測點位置。本計畫設計一個現地試驗，量化位於摩洛哥瓦迪(Wadi Satt)農場的地下水通量估算。當地的地下水來自於摩洛哥東南方的安迪阿提斯山脈，試驗場使用自動化氣壓計水位計進行觀測。

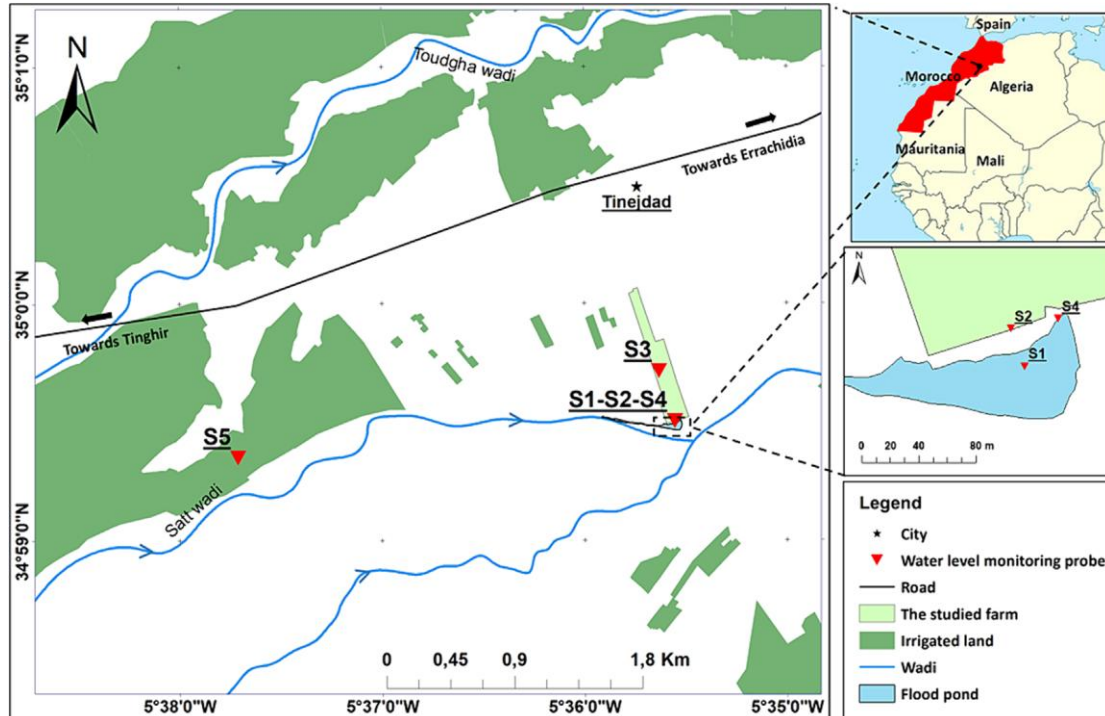


圖 1 研究區域及地下水監測點位置圖

研究區域位於摩洛哥的瓦迪(Wadi Satt)農場，研究區水資源來自

於瓦迪 Wadi 的洪水及摩洛哥東南方的安迪阿提斯山脈(Anti-Atlas Mountains)的地下水。農塘上游集水區面積為 790 km²，年降雨量 140 mm。地下水試驗步驟是藉由建立監測設施及田野調查，由試驗區設置 S1, S2, S3, S4 及 S5 等監測井(點)水位數值，進行分析計算影響圈。井 S1 為設置在農塘的 12 m 深的水位監測井，裝置自動水位記錄器。井 S2 及井 S3(井深度大於 80 m)距離農塘分別為 30 m 及 360 m，用於監測地下含水層水位，S4 監測點水位計設置在農塘中，監測農塘水位，井 S5 為在農塘上游 3 公里，代表水位不受農塘地下水補注影響點。研究期間蒐集 6 場次降雨事件進行分析。依據滯洪池收支水平衡分析，分析指出大部分(56%收集的洪水)的蓄留水是被抽取為灌溉用水，超過 40%水量是以入滲率 90 mm day⁻¹ 入滲地下水及其他損失如蒸發等。農塘水收支平衡式考量入滲及抽水量如式(1)所示：

$$\Delta h_{\text{pond}} = I_{\text{total}} + P/A + E + ET_{\text{palm}} \quad (1)$$

其中， Δh_{pond} 為 S4 水位變化， $I_{\text{total}} = I_{\text{pond}} + I_{\text{well}}$ ， I_{pond} 是池底入滲量(m)， I_{well} 是觀測井 S1 入滲量(m)， P 是灌溉抽取量(m³)， A 為農塘水域面積(m²)， E 為農塘蒸發量(m)， ET_{palm} 為農塘植物蒸發散量(m)。利用農塘水量收支平衡式估算入滲量及抽水量。

$$I_{\text{total}} = a \cdot h + b \quad (2)$$

利用式(1)建立總入滲量 I_{total} 及農塘水位 h 關係，利用洪水期間水位觀測值評估 a 及 b 參數。試驗使用自動化氣壓計水位計，監測容量 6500 m³ 滯洪池的水位，計畫期間 2021-2023 蒐集 6 場洪水事件，監測數據使用在的地下水通量分析。池子的水位系統模擬分析入滲導致之地下水影響半徑少於 360 m。池子的灌溉觀察到地下水補注情況，經由持續抽取數週後，由 2 個相近的洪水事件，看出地表水是進行補注至地下含水層。地下水利用太陽能抽取至農塘蓄存，以重力流灌溉農區作物。應用地下水補注模式進行分析，模式中提供滯洪池的 HVA

曲線函數、長度及深度等參數，含水層之水利傳導係數(K)及蓄水係數(S)等為主要參數，模式是利用 S2 觀測水位及洪水事件觀測值進行參數率定。

計畫執行期間結果顯示：以觀測降雨事件 1 至降雨事件 4 數值分析，滯洪池(S4)的水位及補注井(S1)之水位具相似增加趨勢，在幾分鐘內水位提升到峰值，之後水位趨勢逐漸下降，觀測 S1 水位的下降速度比 S4 水位快。S4 水位因為抽水使用期間，水位呈現階梯式型態分布。本試驗觀測，滴灌(drip irrigation)並無地下水補注成效，地下水水位變化觀測之補注效益，僅在洪水後，觀測其變化。分析結果顯示補注井入滲量低於 $0.7\text{m}^3\text{h}^{-1}$ ，滯洪池的入滲率界在 $1*10^{-3}\sim 9*10^{-3}\text{mh}^{-1}$ 。以滯洪池最大表面積($6,400\text{m}^2$)估算，入滲量超過 $100\text{m}^3\text{day}^{-1}$ ，估算滯洪池入滲率介在 $0.3\sim 1.0\text{m day}^{-1}$ 。灌溉圖觀察到地下水補注情況，經由持續抽取數週後，由 2 個相近的洪水事件，看出地表水是進行補注至地下含水層。這研究展示滯洪池補注地下水的效益，這觀測顯示以洪水補注地下水的效能，受到地下受限含水層影響，建議未來滯洪池進一步擴大使用在集水區尺度，應分析對於下游水資源的負面衝擊。乾旱地區，藉由滯洪池收集雨水，其水量可提供額外的地表水使用及補充地下水層水量，進而能夠緩解灌溉用水導致地下水損耗。

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Conjunctive use of floodwater harvesting for managed aquifer recharge and irrigation on a date farm in Morocco

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ABSTRACT

In arid regions, harvesting floodwater can mitigate irrigation-induced groundwater depletion by providing additional surface water and recharging aquifers. We designed an experimental protocol to quantify these fluxes on a date farm located along the Wadi Satt, whose flow originates from the Anti-Atlas Mountains in south-eastern Morocco. Automatic barometric sensors were used to monitor the water level in a 6500 m³ floodwater harvesting pond and in surrounding boreholes. Six flood events occurred from 2021 to 2023. The pond water balance indicated that most stored water is pumped for irrigation (56% of harvested floodwater). More than 40% infiltrates at a rate of approximately 90 mm day⁻¹, and the remainder evaporated. Analytical modelling of the pond water table system showed that the radius of the piezometric mound resulting from pond infiltration is less than 360 m. Groundwater recharge from the irrigated plot could be observed after two close floods that enabled continuous pumping for several weeks, suggesting that in this specific context, overirrigation using surface water allows the aquifer to be recharged. The hydrological effects of possible future expansion of these ponds at the watershed scale should be analyzed to assess possible negative impacts on downstream water resources.

KEYWORDS

analytical modelling, floodwater harvesting pond, groundwater recharge, Moroccan oasis, spate irrigation, water balance assessment

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利用拉格朗日乘數最佳化設計最小總成本之地下排水網路

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摘要

地下排水系統不僅能有效控制農業用地地下水位，也有助於減緩集中於根區的土壤鹽分問題，特別是在乾旱與半乾旱農業生態系統中。本研究建構了一個在設計限制條件下最小化地下排水系統總成本的最佳化模式，模式採用拉格朗日乘數法作為最佳化方法，以此推導出一通用微分方程式，以求解最具經濟效益的地下排水系統設計方案。

研究發展了一系列設計組合，呈現在不同設計條件下，每公頃地下排水網路的最低成本(美元/公頃)。設計參數包含：側管管徑(dL)為 2.5、5、7.5、10、12.5 公分；水力傳導係數(K)為每日 0.5、1、2、3 和 4 公尺；側管長度(LL)為 100、150、200、250、300 公尺；固定集管長度(LC)為 1000 公尺(假設側管從兩側連接至集管)；排水量(q)為每日 1、2、3、4、5 毫米；開挖深度為 1.5 和 2.0 公尺。在側管長度(LL)為 300 公尺時，不同側管管徑(dL)所計算得的地下排水網路最低成本分別為每公頃 205、246、288、331 和 374 美元，其對應的側管間距為 175、176、177、178 和 179 公尺。

本研究所提出的設計圖表，相較於傳統的管道與抽水井設計方法，能有效降低整體建設成本。研究成果有助於設計人員以更低且更可負擔的成本，在埃及尼羅河三角洲舊耕地及其他類似農業系統中推動地下排水系統。此外，施工期間的品質控管亦是確保地下排水系統長期穩定與永續運作的關鍵環節。

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關鍵字：水力傳導係數、入滲、最佳化模式、鹽度、地下排水系統

註解

隨著氣候變遷、人口成長、都市化及經濟活動增加，全球淡水資源日益短缺。農業為最大的水資源使用部門，全球灌溉用水量佔用水總量的 80%，因此節約用水並提升農業生產效率至關重要。而在乾燥與半乾燥地區，土壤鹽化問題日益嚴重，尤其在埃及尼羅河三角洲長期使用農業回歸水的農業地區，約有 30%至 40%土壤受鹽害影響，進而威脅作物產量與糧食安全。地下排水系統(subsurface drainage system)是一種可有效控制地下水位、減少土壤鹽分累積、提升作物根系發展與減輕植物缺水問題的方法。然而，傳統排水設計方法缺乏經濟效率。因此，本研究透過拉格朗日乘數法(Lagrange Multiplier, LM)建構最佳化模式，以設計出整體成本最低的地下排水網絡，為埃及及其他類似農業環境地區提供經濟可行的地下排水系統。

本研究透過拉格朗日乘數法建構成本最佳化模式，整體地下排水網路成本考量材料費用、安裝費與維護費，並考慮多項設計變數如管徑、深度、間距、水力傳導度、排水率等因子。研究以矩形區域為假設模型，排水系統設計採平行設置的橫向側管與中央收集管，兩側橫向側管接入中央收集管。本研究利用修正 Hooghoudt 公式、Van Beers 公式和 Manning 公式，分別計算設計排水率(q , m/d)、鋪設深度和排水能力(Q , m³/s)，並設置限制條件以確保深度、直徑與間距在農田實際可行範圍內。

在成本函數中，材料費包含管道、濾材、檢查井等；安裝費考慮深度與直徑對施工成本的影響；維護費則以固定百分比處理並不納入最佳化過程。本研究運用拉格朗日乘數法進行求解，使得總成本在滿足一系列限制條件下達到最小值，並以埃及尼羅河三角洲地區的實際土壤與經濟參數進行設計圖表。

透過模式運算，研究團隊建立了一系列涵蓋不同側管管長(100、150、200、250、300 m)、直徑(2.5、5、7.5、10、12.5 cm)、水力傳導度 K (0.5、1、2、3、4 m/d)、排水率 q (1、2、3、4、5 mm/d)與開挖深度(1.5、2.0 m)等

設計條件的成本。根據結果顯示，當側管管長為 300 公尺時，最低總成本依直徑由小至大分別為：205、246、288、331 及 374 美元/公頃，而對應最佳橫向間距則為 175、176、177、178 和 179 公尺。

與傳統方法相比，應用本研究最佳化模式所設計之排水系統能降低材料與安裝成本。此外，結果顯示，在維持合理地下水位與灌溉效率前提下，較大的管徑與較深的安裝雖增加個別單位成本，但可降低管道總數與間距，最終使總成本下降。這些設計為規劃者提供多種經濟且可行的選項，有助於在不同農田條件下進行彈性設計。

本研究開發出一套可應用於乾旱與半乾旱地區的地下排水系統設計最佳化方法，透過拉格朗日乘數法與土壤和水文參數整合，建立最小成本模式並提供清晰實用的設計。結果顯示，經由此方法設計的排水系統成本顯著低於傳統經驗法，適用於尼羅河三角洲等地區，亦可推廣至其他土壤與氣候條件相似的地區。研究建議，實務施工時須重視品質管控，以確保系統長期效能與經濟效益。本研究設計架構與計算工具對推動水資源永續利用與農業現代化具有重要意義。

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Design of subsurface drainage network with minimum overall cost using Lagrange multiplier optimization

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ABSTRACT

Subsurface drainage is effective for not only controlling groundwater levels in agricultural lands but also alleviating soil salinity localized at the root zone, especially for arid and semi-arid agro-ecosystems. In this research, an optimization model that minimizes the overall costs of subsurface drainage systems subjected to design constraints was formulated. The Lagrange multiplier method for optimization was utilized to derive a general differential equation for obtaining the most economical design of the subsurface drainage system. Design charts for the minimum cost of the subsurface drainage network ($\$ \text{ha}^{-1}$) for lateral diameters (dL) of 2.5, 5, 7.5, 10 and 12.5 cm; hydraulic conductivities (K) of 0.5, 1, 2, 3 and 4 m day^{-1} ; different lateral lengths (L_L) of 100, 150, 200, 250, and 300 m; a constant collector length (L_C) of 1000 m (assuming laterals join the collector from both sides); drainage recharge (q) values of 1, 2, 3, 4 and 5 mm day^{-1} ; and excavation depths of 1.5 and 2.0 m were developed. The minimum computed subsurface drainage network (SSDN) costs observed at a lateral length (L_L) of 300 m were 205, 246, 288, 331 and 374 ($\$ \text{ha}^{-1}$) for lateral diameters of 2.5, 5, 7.5, 10 and 12.5 cm, respectively, corresponding to lateral spacing of 175, 176, 177, 178 and 179 m. The suggested charts for the optimum design of a subsurface drainage system have lower overall costs than using conventional design approaches for pipelines and tube wells. The results will support solutions for designers to implement subsurface drainage systems with less and more affordable expenses in the old lands of the Nile delta of Egypt and other regions with similar agrosystems. Quality control during construction is very necessary for guaranteeing the effective and sustainable performance of subsurface drainage systems for many years.

KEYWORDS

hydraulic conductivity, infiltration, optimization model, salinity, subsurface drainage system

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運用分析網路程序法及地理資訊系統評估排水系統在農業水資源 多元利用之可行性

Parvin Zolfaghary¹, Mahdi ZakeriNia¹, Hossein Kazemi²

摘要

在永續農業議題中，非傳統水資源的利用涉及多因子的分析程序。為發掘有價值之關鍵因子，必須使用先進的分析方法，例如，分析網路程序法(ANP)。分析網路程序法的相關因子具非獨立性及有內部與外部群聚交互關係。這計畫考量技術-經濟及環境因子，運用分析網路程序法及地理資訊系統，探討位在伊朗西哥勒斯坦省的迦巴赫利大排水資源運用，評估迦巴赫利大排水資源多元利用之可行性。分析在西哥勒斯坦省種植油菜、大麥、棉花及小麥等耐鹽或半耐鹽作物之可行性。技術-經濟之關鍵因子包括灌溉水源是否充足、水資源可及性及土地特性是否適合作物生長等。環境因子部分則考量水質、土壤、作物敏感度及含水層脆弱性等因子。分析結果顯示迦巴赫利大排水資源用在種植油菜是最佳作物。這個研究提供可靠的決策支援架構，在環境危害最小化種植各種作物，其排水水資源進行回收再利用。

關鍵字：分析網路程序法、決策、排水系統水資源、地理資訊系統、水資源再利用

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註解

隨著全球人口成長，水資源需求亦隨之提高。這導致非傳統之替代水源(例如，大排水資源、廢水再利用及海水淡化等)運用在最大水資源需求的農業使用上。大排的排水常含有較高有機物質(BOD)、營養鹽或鹽度，較高BOD及營養鹽是導致水體污染及造成優養化原因之一。若循環再利用大排的排水，一方面可以節省水資源，另一方面，可以增加生產量，並降低水域環境營養鹽負荷。對於較高鹽分之排水，可考量與低鹽份水混和，以減少鹽分濃度，降低對於作物之影響。在永續農業議題中非傳統水資源的利用是涉及多因子的分析程序。為發掘有價值之關鍵因子，必須使用先進的分析方法，運用分析網路程序法(ANP)，分析網路程序法的相關因子具非獨立性及有內部與外部群聚交互關係。

本計畫考量技術經濟及環境因子，運用分析網路程序法及地理資訊系統，研究地點在伊朗西哥勒斯坦省的迦巴赫利大排，設定迦巴赫利大排供水地區範圍為距離大排 5 公里內為供水區域。西哥勒斯坦省監測當地大排水質。農排水再利用在管理層面，除了考量水質及土壤等環境因子外，亦須將水資源可及性之經濟因子納入評估。技術及經濟之關鍵因子包括灌溉水源是否充足、水資源可及性及土地特性是否適合作物生長等。分析網路程序法(ANP)包含多準則決策分析(Multi-criteria decision analysis, MCDA)功能，並與地理資訊系統搭配應用在這些多面向、多維度之問題分析上，其使用多準則決策分析分析及地理資訊系統圖層分析，提供高效能環境，整合多因子在空間分布的問題，有助於可行性的決策分析，參圖 1。分析網路程序法(ANP)，分析網路程序法的相關因子具非獨立性及有內部與外部群聚交互關係，應用在非傳統之替代水源運用可行性分析。

分析過程需蒐集以下基本資訊，包括 (1) 為達成目標之問題確認；(2) 說明相關主要及次要因子，及其關聯特性；(3) 準備相關 GIS 圖層；(4) 分類及製作標準圖層；(5) 確定主要因子及次要因子數值；(6) 計算 ANP 之主要

因子及次要因子權重;(7) 應用 ANP 後，進行圖層分類。

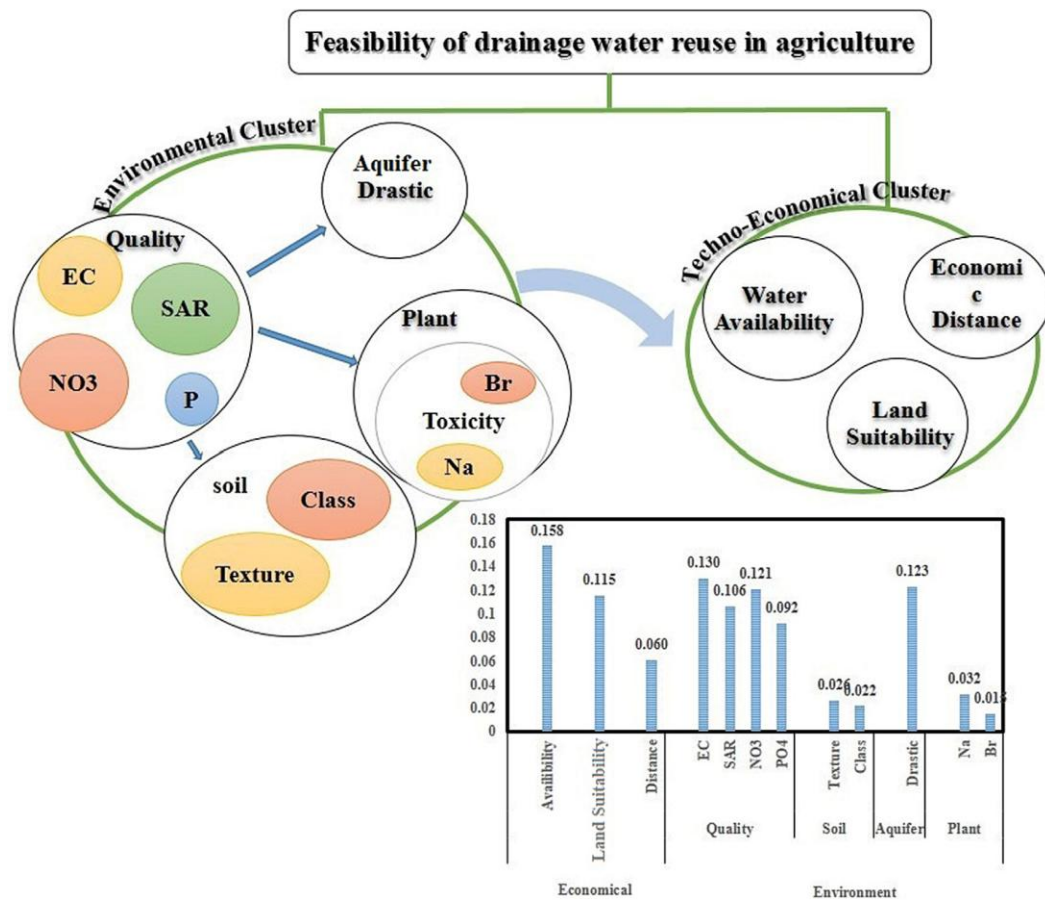


圖 1 分析網路程序法(ANP)架構模型及分析因子

分析網路程序法(ANP)架構模型使用在判斷分析 4 種作物包括油菜、大麥、棉花及小麥等使用大排用水之可行性。決策程序分析含鹽分大排排水與地表水混和分析情境，藉由四種情境包括 100%、75%、50%及 20%。決策架構目標是以水資源循環再利用及最小化環境衝擊為目標。主要考量環境因子：水質、土壤、環境保護措施及植物。水質因子考量包導電度(EC)、鈉吸附比(sodium adsorption ratio, SAR)、硝酸鹽(NO₃)及磷(P)等水質標準。利用既有土壤調查數據，蒐集土壤的鹽度及含鈉濃度等數據，並 GIS 圖層化。環境保護措施考量地下水保育，因為當地飲用水來源為地下水，高登(Gorgan)集水區地下水含水層圖層應用在本計畫中。針對作物毒性，土壤中鈉含量影響灌溉用水。技術及經濟方面，探討灌溉水源是否充足、水資源可及性及土

地特性是否適合作物生長等。灌溉水源是否充足是指具有在低導電度水資源，有利於水資源混和方案運用，水資源可及性是考量成本效益因素，以管線傳輸水資源，連結供水及需水地區，使其具有成本效益。土地特性以農藝生態圖層包含環境資訊，土地利用情況、生物多樣性等，藉以判斷是否適合作物生長。上述判斷因子，圖層化後應用於決策分析系同，在分析網路程序法(ANP)架構模型，分析其重要性，以利支援決策。

應用模式分析結果顯示迦巴赫利大排水資源用在種植油菜是最佳作物，小麥是最不適合的作物。迦巴赫利大排水質在該省 6 個大排中，水質是最好的，根據成本與效益考量，分析 4 個排水混和情境，運用在可行性判斷。這個研究提供可靠的決策支援架構，在環境危害最小化種植各種作物，其排水水資源進行回收再利用。

本研究調查大排水水資源運用在農業之可行性，整合及比對空間資訊，應用分析網路程序法(ANP)架構模型及 GIS 空間圖層，產出最適合使用大排水區域。研究區域中，大排水質的鹽度是一個關鍵因子，藉由與其他低鹽度進行混和，其成為情境分析，改善耐鹽作物是用之水質條件，獲得適合的區域。這個研究提供可靠的決策支援架構，在環境危害最小化種植各種作物，其排水水資源進行回收再利用。

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Feasibility of utilizing recycled drainage water in agriculture using an analytical network process (ANP) and geographic information system (GIS)

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ABSTRACT

Utilizing unconventional water for sustainable agriculture is a multi-criteria process. Decision-making in such problems is based on finding the value of various criteria using advanced methods, for example the analytic network process (ANP). ANP is usually preferred in cases where the criteria are not independent and have intra-/intergroup relationships. Considering technoeconomic and environmental criteria, the ANP structure was used in this study to investigate the feasibility of utilizing Chapaghli drainage water in western Golestan Province, Iran, for cultivating tolerant and semi-tolerant crops, including canola, barley, cotton and wheat, using GIS software. Irrigation water availability, techno-economic distance and land suitability for cultivation were selected as techno-economic criteria, while irrigation water quality, soil, plant sensitivity and aquifer vulnerability were selected as environmental criteria. The results show that canola is the best crop for cultivation with Chapaghli drainage water. This study provides a reliable decision-making infrastructure related to the recycling of drainage water for various cultivars in an area where environmental hazards are minimized.

KEYWORDS

ANP, decision-making, drainage water, GIS, water reuse

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巴西東南部應用處理後生活污水結合地下滴灌方式灌溉甘蔗之溫室氣體排放研究

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摘要

減少溫室氣體排放、回收水再利用於灌溉及獲得高農作產量是當前農業面臨的主要挑戰之一。因此，本研究旨在分析以處理後生活污水及地表水灌溉甘蔗時所產生的溫室氣體排放量，包括二氧化碳、氧化亞氮和甲烷排放，並比較有無施肥灌溉的情況與無施灌(對照組)之間的差異。在無灌溉、僅進行追肥的對照組中，使用污水或礦物氮肥所進行的氮肥施用，分別使 N₂O-N 排放量減少了約 38 %和 66 %。

歷次的生活污水處理均觀察到吸入 C-CH₄吸收的現象，其對總排放量之貢獻未具統計顯著性，歷次的生活污水處理的 C-CH₄吸收平均值約為 54.56 克/公頃。使用處理後生活污水並搭配礦物氮肥灌溉的甘蔗，其二氧化碳當量排放量最高，高達 15.12 公噸 CO₂eq/公頃。而使用不含 N 礦物的生活污水處理後的再生水(總溶解固體, TDS)施灌處理，其「可回收理論糖產量與二氧化碳當量排放比」最高，為 2.63 公噸可回收糖/每公噸 CO₂eq。使用生活污水處理後的再生水(TDS)或地表水進行灌溉並配合肥灌的處理，皆提升了甘蔗的莖部生物量及糖產量，並使理論可回收糖的產量更高。

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關鍵字：碳當量、施肥灌溉、局部灌溉、氧化亞氮、糖產量

註解

在面對氣候變遷與全球水資源緊張的挑戰，農業領域正承擔著「減碳」、「節水」與「增產」的多重任務，氣候變遷已加速改變許多地區之農業生產體系，例如灌溉面積的增加，而灌溉面積和氮肥的增加可能導致土壤中甲烷(CH₄)和氧化亞氮(N₂O)排放加劇；灌溉方法是確保永續和公平糧食安全的有效措施，灌溉措施和肥料使用是學者提出適應氣候變遷的可行方法之一，土壤水分含量和氮肥是影響土壤中氧化亞氮(N₂O)排放的重要因素，過去的研究也驗證氮肥施用量的增加會提高作物(玉米)灌溉的氧化亞氮(N₂O)排放，排放速率關鍵為土壤水分含量。地下滴灌(Subsurface Drip Irrigation, SDI)減少灌溉區域的溫室氣體排放潛力，透過高頻灌溉和低流量的方式減少了土壤表層的濕潤及濕乾交替循環，進而保持土壤濕度的穩定性，相較於傳統溝灌方法，SDI具有大幅降低溫室氣體排放的潛力。其次，透過滴灌方法施灌水量時，同時施灌有機肥料，與溝灌相比，有減少 N₂O 排放和反硝化速率的特點。

本篇論文的研究的動機十分明確，針對巴西該國的重要經濟作物-甘蔗的生產過程中，因高需水量特性與傳統農業溝灌方式導致不僅耗水量高，伴隨著溫室氣體排放，尤其是氮肥施用後造成的氧化亞氮(N₂O)排放，導致對氣候變遷影響甚鉅。因此，尋找一種能兼顧「水資源再利用」、「減碳排」及「農產增收」的永續農業灌溉模式，是當務之急。而處理後的生活污水，具備基本灌溉水質標準，同時也含有一定量的氮、磷等養分，若能妥善利用，將有助於降低對礦物肥料的依賴，並促進作物生長。

針對前述重點特性，本篇研究提出的策略之一是使用地下滴灌(SDI)搭配生活污水處理後的再生水(TDS)於巴西東南部進行主要作物-甘蔗灌溉評估，分析對甘蔗田溫室氣體排放與作物產量之影響。同時比較灌溉與非灌溉、有無施肥等多種處理下之環境與生產效益。以探討再生水在灌溉應用上的潛力及其對溫室氣體排放的影響。

本篇論文的試驗地點位於巴西東南部地區的甘蔗種植田區，該區域屬熱帶氣候，適合甘蔗種植並具代表性，試驗已於 2012 年 9 月到 2013 年 8 月期間完成，試驗設計重點除了採用地下滴灌(SDI)系統搭配生活污水處理後的再生水進行多組不同處理變因的對照試驗，包括：1.灌溉水源：地表水 vs. 處理後生活污水、2.是否施肥：無肥、僅使用污水、再生水搭配礦物氮肥等、3.灌溉與否：灌溉試驗組 vs. 無灌溉對照組。為評估前述試驗灌溉甘蔗所產生的溫室氣體排放情形，試驗過程監測指標涵蓋 CO₂、N₂O、CH₄ 等 3 種溫室氣體的排放量，同時記錄甘蔗生長產量及可回收糖含量等農藝性狀，以評估不同處理方式的碳效率與經濟產值。

本篇論文透過連續觀測與數據分析，作者發現各項處理在溫室氣體排放與甘蔗生產上表現迥異：

1. 氧化亞氮(N₂O)排放：在對照組(無灌溉、僅追肥)下，使用再生水與礦物氮肥的處理組，其 N₂O 排放量分別下降約 38%與 66%，顯示生活污水處理後的再生水(TDS)中的養分能替代部分化肥，降低排放風險。
2. 甲烷(CH₄)吸收：所有污水灌溉處理皆觀察到 CH₄ 的淨吸收現象，平均吸收量為 54.56 g/ha，儘管統計上未達顯著性，但仍具研究價值。
3. 碳當量排放(CO₂eq)與碳效率：使用生活污水處理後的再生水(TDS)搭配礦物氮肥的組別，其總溫室氣體排放為最高(15.12 噸 CO₂eq/ha)，顯示雖然作物產量高，但環境成本也隨之增加。相較之下，單獨使用不含氮肥的生活污水處理後的再生水(TDS)處理組，卻展現出最佳的碳效率，其每單位 CO₂ 排放可換得 2.63 噸可回收糖，成效最佳，兼顧環境與生產效益。
4. 農業生產成果：無論使用地表水或生活污水，搭配灌溉與施肥的處理組皆顯著提升了甘蔗莖部生物量與糖產量，再生水的灌溉效益獲得驗證。

這篇論文提供了極具參考價值的田間試驗數據與實務觀察，實證顯示經處理後的生活污水(再生水, TDS)不僅能安全應用於農業灌溉，其所含養分亦具備替代部分化肥的潛力，有助於提升作物生產效率。然而，本研究也

提醒我們，若在再生水灌溉同時施用過量氮肥，反而會導致碳排放增加，形成環境負擔。因此，推動再生水應用於農業灌溉時，應特別重視施肥策略的規劃，兼顧農業生產與環境永續的平衡。

此外，本篇研究也點出灌溉技術選擇的重要性，例如地下滴灌技術可有效降低地表及土壤水分蒸發損失，並促進局部施肥與溫室氣體減量。雖然該項試驗早在 2012~2013 年完成，但其核心概念與技術應用與目前台灣積極推展的智慧灌溉系統高度契合。在面對氣候變遷衝擊、國際減碳壓力、水資源短缺與農業永續等多重挑戰下，透過整合再生水利用與先進灌溉技術，無疑是台灣農業發展下一階段可行且值得推動的方向。

摘要翻譯及註解：陳豐文 研究員

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Greenhouse gas emission of sugarcane irrigated with treated domestic sewage by subsurface drip in Southeast Brazil

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ABSTRACT

Reducing greenhouse gas emissions, reclaiming water for irrigation, and obtaining high agricultural yields are among the main agricultural challenges; therefore, this study aimed to analyse greenhouse gas emissions, including carbon dioxide, nitrous oxide, and methane emissions, in sugarcane irrigated with treated domestic sewage and with surface water, both with and without nutritional supplementation via fertigation, and in a non-irrigated control. Regarding the non-irrigated control with topdressing fertilization, nitrogen fertilization carried out by sewage or mineral sources decreased N-N₂O emissions by nearly 38% and 66%, respectively. C-CH₄ influx was found in all treatments with a non-significant contribution to the total emissions, representing average values between treatments near - 54.56g C-CH₄ ha⁻¹. The crop irrigated with treated domestic sewage plus N minerals shows significantly the highest C-CO₂ equivalent emissions (15.12 Mg CO₂eq ha⁻¹), and the treatment irrigated with sewage without N minerals showed the highest relation between the yield of theoretical recoverable sugar and C-CO₂ equivalent emissions (2.63 Mg recoverable sugar Mg⁻¹ CO₂eq ha⁻¹). The treatments using sewage or with surface water irrigation, both fertigated, increased the stalk biomass and sugar yield, with a higher yield of theoretical recoverable sugar.

KEYWORDS

carbon equivalent, fertigation, localized irrigation, nitrous oxidesugar yield

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中國華南地區以農村生活污水再生灌溉對稻田土壤性質、水分利用及氮肥利用的影響

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摘要

農村生活再生水(RDRW)應用於農業灌溉，是緩解水資源供需矛盾的有效方式。本篇研究設置了 4 種灌溉水源(初級與二級處理水、純水及以河川水作為對照組)，並採用 3 種湛水深水位調控方式(低水位、中水位與高水位控制)，透過田間試驗、實驗室分析與數值分析相結合的方法，探討 RDRW 灌溉及其再利用對水稻田土壤性質、水分利用、氮肥利用及稻米產量之影響。

研究結果顯示，使用 RDRW 灌溉與河川水灌溉相比較，發現以 RDRW 施灌下之土壤 pH(0~40 cm)、電導度(EC)及有機質(OM)含量(60~80 cm)均有所增加，且銨態氮(NH₄⁺-N, 0~20 cm)與硝酸鹽氮(NO₃⁻-N, 40~60 cm)含量呈現累積。在高水位調控條件下，NH₄⁺-N 與 NO₃⁻-N 含量上升，呈現與低湛水深、中湛水深管理條件下相反的變化趨勢。在 RDRW 灌溉條件下，水分與氮肥利用效率以及稻米產量均顯著提升；與使用河川水源灌溉成果相比較，灌溉用水利用效率(IWUE)、氮肥利用效率(NUE)與稻米產量分別提升了 48%~70%、10%~22% 和 5%~13%。

此外，透過結構方程模型(SEM)建立的徑路分析顯示灌溉水量(IWA)對 NUE 與 NH₄⁺-N 有顯著正面影響，但對 IWUE 與 EC 則呈顯著的負面影響。而 NUE、IWUE、NO₃⁻-N 與 EC 均對稻米產量有顯著正面影響。IWA 透過

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IWUE 對產量的徑路呈現完全中介效應；而 IWA 經由 EC 影響產量及 NUE 經由 EC 影響產量的路徑則均為部分中介效應，對應的影響比例分別為 27.9 %與 25.0 %。

關鍵字：電導度、氮素、有機質、再生水灌溉、結構方程模型、水位調控、用水效率

註解

水資源短缺是全球共同面臨的挑戰，本篇研究有鑑於中國水資源短缺問題日益明顯，因工業與生活用水的大量增加，導致農業灌溉用水的年缺口已達到 600 億立方公尺，且逐年增加中；同時農業非點源污染問題也伴隨著農村生活污水排放量的上升而變得顯著。面對水量及水質的雙重挑戰，生活污水經處理後再利用於農業灌溉的做法是本篇著重的水資源短缺及水質問題的對應作法。目前回收水的主要用途為農田灌溉、景觀水補充和地下水補充；由於都會區及農村的生活污水特性仍有差異及區隔，農村生活污水是指居民生活過程中產生的糞便、洗滌水、洗澡污水及廚房污水，農村生活回收水(RDRW)乃通過工程與管理措施處理後，達到特定利用水質要求的農村生活污水，與都會區生活污水處理後的回收水相比，RDRW 具有水質差異小、水源分散、氮與磷含量高及可生物降解性好等特點，通常不含重金屬等有毒物質，可作為肥料資源使用，也更容易保障灌溉再利用的安全性；然而針對農村生活污水處理後回收再利用於灌溉的研究相當少，對於回收水灌溉和排水調控對水稻土壤性質、以及水、氮和鹽的交互作用機制的影響研究仍然不足。因此本篇研究以中國華南地區的金華市永康農村家庭污水回收水為試驗對象，施灌作物以水稻為主，將水位調控作為灌溉排水的控制指標，分析回收水灌溉對水稻田土壤性質指標、水和氮的利用指標以及產量的影響。

本篇研究的試驗設計乃設置 400 CMD 的家庭污水處理站作為農村生活再生水(RDRW)主要來源，試驗田區由 36 個標準測試田區(20 × 5 m)組成，田埂高度統一設置為 30 mm；為評估農村生活污水經處理後回收應用於稻作灌溉對農地土壤的影響，使用了 4 種灌溉水源進行比較，包含使用初級及二級處理程序之農村生活再生水(RDRW)、純水和河川水源，這 4 種水源均有符合灌溉水質標準，透過 3 種田間湛水深 (低、中、高)的水位調控觀測，評估施灌於水稻後的土壤 pH 值、電導率(EC)、銨態氮(NH₄⁺-N)、硝態

氮($\text{NO}_3\text{-N}$)和有機物(OM)等土壤性質指標變化差異。

經由 2020 ~ 2021 年的試驗成果有幾項重要發現，茲節錄分述如下：

1. 不同灌溉水源和水位調控下對土壤 pH 的變化：使用初級處理後的農村生活再生水(RDRW)施灌時，0 ~ 40 cm 土壤層的 pH 值上升 2.8 ~ 3.6 %，若使用二級處理後的農村生活再生水(RDRW)、純水或河川水源施灌時，土壤層的 pH 值均無顯著變化。
2. 對土壤電導率(EC)的影響：初級及二級處理後的農村生活再生水(RDRW)施灌後，所有土層(0 ~ 80 cm)的 EC 值均顯著增加，使用純水及河川水施灌，則僅於土層 0 ~ 20 cm 範圍的 EC 值有所增加，總體來說，土壤 EC 值因使用農村生活再生水(RDRW)施灌水稻田而顯著增加，有助於增強土壤中可吸附離子的解離和交換特性，增強各種離子與土壤膠體間的相互作用強度，有利於促進作物吸收與利用效率。
3. $\text{NH}_4^+\text{-N}$ 和 $\text{NO}_3\text{-N}$ 含量變化：使用初級處理後的農村生活再生水(RDRW)施灌後，0 ~ 20 cm 和 40 ~ 60 cm 土層的 $\text{NH}_4^+\text{-N}$ 含量分別增加 9 % 和 14 %；但使用二級處理後的農村生活再生水(RDRW)、純水及河川水施灌後，各土層的 $\text{NH}_4^+\text{-N}$ 含量反而呈現減少現象(分別為 24 %、13 % 和 36 %)。比較不同的湛水深操作，中低湛水深調控條件顯示稻田 $\text{NH}_4^+\text{-N}$ 含量變化呈現下降趨勢(21 ~ 22 %)，維持高湛水深時反而增加(7%)。結果顯示回收水帶來的氮源在高水位條件下導致使用初級處理後的農村生活再生水(RDRW)施灌的各土層中 $\text{NH}_4^+\text{-N}$ 含量呈現增加趨勢。
4. 稻田土壤的 $\text{NO}_3\text{-N}$ 含量相對 $\text{NH}_4^+\text{-N}$ 較低，且波動較小，使用初級處理後的農村生活再生水(RDRW)施灌，0 ~ 40 cm 土層中的 $\text{NO}_3\text{-N}$ 含量呈現增長趨勢(12~34 %)，60~80 cm 土層則為下降趨勢(32 %)，稻田中的 $\text{NO}_3\text{-N}$ 含量與湛水深高度呈正比；而使用二級處理後的農村生活再生水(RDRW)、純水及河川水源施灌後，各土層中的 $\text{NO}_3\text{-N}$

N 含量顯示下降趨勢，並以河川水源施灌的田區波動較大；進一步調整湛水深為中低水位時，土壤中的 $\text{NO}_3\text{-N}$ 含量則普遍下降(17~24%)，反之調整為高湛水深時，則含量普遍提高(19%)。

5. 以處理過的家庭污水(RDRW)進行稻作施灌，促使稻田土壤由酸性趨向中性，電導度(EC)顯著增加趨勢，氨態氮($\text{NH}_4^+\text{-N}$)主要累積在 0~20 cm 土層，而硝酸態氮($\text{NO}_3\text{-N}$)則累積於 40~60 cm 土層，其存在一定的淋洗風險；深層土壤的有機質(OM)含量亦有所增加。

本篇研究的田間試驗成果豐富，除了對土壤的性質進行廣泛影響探討外，論文亦提及用水效率及產量的影響，例如以低湛水深為基準，調高湛水深為中水位及高水位時，灌溉水量(IWA)分別增加了 13%與 112%。使用初級或二級處理的農村生活再生水(RDRW)灌溉後，灌溉水利用效率(IWUE)和氮肥利用效率(NUE)均有所提升，且稻米產量明顯增加。相較於河川水源灌溉條件做比較，IWUE 分別提升 1.70 倍、1.65 倍；NUE 提升 19%、22%；稻米產量則提升 14%及 13%。灌溉水量(IWA)對氮肥利用效率(NUE)與氨態氮($\text{NH}_4^+\text{-N}$)有顯著正向影響，但對灌溉水利用效率(IWUE)與電導度(EC)具顯著負向影響。pH 值對($\text{NH}_4^+\text{-N}$)與 EC 有顯著負向影響；而 NUE、IWUE、 $\text{NO}_3\text{-N}$ 與 EC 則對稻米產量有顯著正向影響。

本篇研究的最大的啟發是全球面對缺水危機，如何提供量足質優的水資源以滿足不同標的用水的需求，是一項重大挑戰；尤其生活用水、工業用水及農業灌溉用水等 3 大用水標的對於質量的要求明顯不同，在有限的天然水資源限制下，具備可再利用潛力的放流水(或稱再生水)的非常規用水益顯重要。然而放流水來源包含工業廢水及公共生活污水等 2 大類；若將放流水視為可再生利用於農業灌溉的潛在用水水源，則工業廢水因具有重金屬污染及其他複雜有毒污染物質的潛在疑慮，因此必須嚴禁使用工業廢水處理後的放流水作為農業灌溉用水，僅考量使用生活污水處理後的放流水應於農業灌溉的可行性。

國內除了缺水危機、尚存在部分河川水體不佳的狀況，放流水的再利用

可能是解方之一；如何進一步使用生活污水經處理後的放流水作為灌溉用水來源之一，推動前須進行審慎科學評估，謹慎考量農業生產各面項的條件，包含用水單位的水源管理操作及水質條件的符合程度、農民關心的作物生長、農產品產量及銷售問題、民眾關心的食安問題、及長期使用下對於農地或土壤環境的影響等均要綜合評估考量；然而國內外的研究對於放流水再生利用於水稻灌溉後對於農地土壤及環境的影響研究甚為缺乏，而本篇研究恰好以現地試驗方式探討處理後的農村生活污水再生應用於稻作灌溉，並針對用水效率、氮肥使用效率及 5 項土壤指標的影響變化進行探討，雖本篇研究的田間試驗期間僅為 2 年，但其研究成果及作法極具參考價值，可作為國內後續推動以生活污水放流水應用於農業灌溉時的長期農地評估做法之借鏡。

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Effect of rural domestic sewage regeneration irrigation on paddy soil properties and water and nitrogen utilization in southern China

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ABSTRACT

Rural domestic reclaimed water (RDRW) for agricultural irrigation is an effective way to alleviate the contradiction between the supply and demand of water. In this research, four kinds of irrigation water sources (primary and secondary treated water [R1 and R2], purified water [R3] and river water [CK]) and three kinds of water level regulations (low, medium and high water level control [W1, W2 and W3]) were set to study the impact of RDRW irrigation and its reuse on the properties of paddy soil, water and nitrogen utilization and yield of rice through a combination of field experiments and laboratory and numerical analysis methods.

The results showed that compared with river water (CK) irrigation, pH (0 ~ 40 cm), electrical conductivity (EC) and organic matter (OM) content (60 ~ 80 cm) increased, and ammonium-nitrogen ($\text{NH}_4^+\text{-N}$) (0 ~ 20 cm) and nitrate-nitrogen ($\text{NO}_3^-\text{-N}$) (40 ~ 60 cm) content accumulated under RDRW irrigation. Under high water level regulation (W3), $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ content increased, showing the opposite changing trend compared with W1 and W2 regulations. With RDRW irrigation, water and nitrogen use efficiency and rice yield were significantly increased. Under RDRW irrigation, irrigation water use efficiency (IWUE), nitrogen use efficiency (NUE) and rice yield were increased by 48 % ~ 70 %, 10 % ~ 22 % and 5 % ~ 13 %, respectively, compared with CK irrigation.

In addition, path analysis established by structural equation modelling (SEM) showed that the irrigation water amount (IWA) had a significant positive impact on NUE and $\text{NH}_4^+\text{-N}$ but had a significant negative impact on IWUE and EC. NUE, IWUE, $\text{NO}_3^-\text{-N}$ and EC had a significant positive impact on yield. The path of IWA => IWUE => yield showed a complete mediation effect, the path of IWA => EC => yield and NUE => EC => yield both showed a partial mediation effect, and the effect size was 27.9 % and 25.0 %, respectively.

KEYWORDS

electrical conductivity, nitrogen, organic matter, reclaimed water irrigation, structural equation model, water level regulation, water use efficiency

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應用不同灌溉水量與處理後城市污水以建立飼料玉米產量 - 用水函數

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摘要

本研究旨在透過不同程度的灌溉與處理過的城市污水，建立飼料玉米的產量-用水函數。研究於 2019 與 2020 年 5 月至 8 月期間，在馬爾夫達什特市政污水處理廠的田間進行，採完全隨機區集設計，共設 12 種處理組合，3 次重複，包含兩個主要因素：(a) 傳統的缺水灌溉管理，共 4 個水量層級（全量灌溉 [FI, 100% 灌溉需求]，以及分別為灌溉需求 40%、60%、80% 的缺水灌溉）；(b) 污水使用方式共 3 個層級（污水 [WW]、井水與污水 1:1 混合水 [50/50]、井水 [W]）。研究使用統計評估模型，以建立與評估產量-用水函數，並分析相對產量減少與相對耗水減少之關係。

三個生育期的產量-用水函數統計評估結果顯示：在營養生長期，葉部產量的產量-用水函數具相對優勢；在開花期則為莖部產量的用水函數；在穀實成熟期則以總乾物質的產量-用水函數最具代表性。三個生育期的總乾物質產量反應係數 (K_y) 分別為 0.38 (營養生長期)、0.52 (開花期) 與 0.63 (成熟期)，顯示玉米對缺水最敏感的階段為穀實成熟期。

交互作用分析結果指出，在 WW-FI 處理（使用污水的全量灌溉）下，營養生長期、開花期的總乾物質產量與穀實成熟期的穀粒產量分別達到最高值，分別為 7260、9857 與 3158 公斤/公頃；而在 W-DI60 處理（使用井水且灌溉量為需求的 60%）下，產量最低，分別為 5052、6069 與 1508 公斤/公頃。研究結果顯示，在傳統缺水灌溉條件下使用污水對飼料玉米具有正面效益，因此建議推廣此做法。

關鍵字：農業、缺水灌溉、飼料玉米、回收、非常規水、產量

註解

本研究針對半乾旱地區飼料玉米生產所面臨的水資源壓力問題，評估城市處理後污水(treated municipal wastewater, TWW)在灌溉應用中的效益，並建構不同生育階段下飼料玉米的產量-用水函數，進一步探討水量、水質與生長期交互作用對產量與水分利用效率的影響。試驗於 2019 與 2020 年 5 至 8 月期間，在伊朗 Fars 省 Marvdasht 市政污水處理廠旁設置試驗田，並以完全隨機區集設計實施田間試驗，設置四種灌溉量處理與三種灌溉水源，共 12 種處理組合，每處理設三次重複。

研究區位於氣候溫和但乾旱少雨的地區，長年水資源供應緊張，極具代表性。灌溉方式採用滴灌系統以精準控制水量，並依據蒸發皿蒸發量與當地氣象資料估算作物需水量。三種水質處理分別為處理後城市污水(WW)、井水與污水 1:1 混合水(50/50)以及純井水(W)。田間調查依據飼料玉米三個主要生育階段：營養生長期、開花期與穀實成熟期，量測不同部位(總乾物質、莖、葉與穀粒)之生物量，並建立其與灌溉水量之產量-用水函數模型。

研究結果顯示，各生育階段的產量皆與灌溉水量呈顯著正相關，三個階段皆可建立具高度線性相關之水分-產量函數，說明水分投入是決定玉米產量的主要因子。不同水質與灌溉量的交互作用明顯影響玉米在各生育期的生長表現，其中以全量灌溉搭配處理後污水的組合產量表現最佳，特別是在開花期與成熟期，對總乾物質與穀粒產量的促進作用最為顯著。相較之下，使用純井水且灌溉量低的組合處理，則在所有生育期的產量皆顯著下降，反映缺水與水質雙重限制對作物生產的不利影響。

進一步透過 Doorenbos and Kassam 模型分析相對產量減少與相對灌溉水減少之關係，可得出各生育期的產量反應係數(Ky)，用以判別作物對缺水的敏感程度。結果指出，飼料玉米在穀實成熟期對水分最為敏感，其次為開花期，營養生長期的敏感度則相對較低，顯示後期水分供應對最終產量

具有關鍵性影響。此外，針對穀實成熟期不同部位的 Ky 值分析亦指出，穀粒的 Ky 值高於莖與葉，進一步證實穀粒產量最易受到水分不足的抑制。

在水分利用效率（Water Use Efficiency, WUE）方面，研究發現即便在缺水灌溉情境下，若搭配使用處理後城市污水，仍可維持良好的產量表現並顯著提升 WUE。此一現象推測與污水中所含有的有機質與植物營養元素有關，有助於促進植株吸收與生長，部分補償因灌溉量減少所造成的水分壓力。此外，污水中氮、磷等可利用養分的再輸入，也有助於提升系統整體資源使用效率。因此，在水資源匱乏區域，透過結合減量灌溉與營養回收型灌溉水源，將可兼顧節水與產量維持。

模型評估方面，本研究亦驗證所建立的各項水分-產量函數的準確性與實用性。透過模型效率（EF）、決定係數（ R^2 ）、均方根誤差（RMSE）與殘差質量係數（CRM）等指標進行誤差分析，結果顯示大多數模型皆具有良好的一致性與預測力，尤其是開花期與成熟期的總乾物質與莖部產量函數，其模型效率指標表現優異。這表示該研究所建立之線性模型具實務應用潛力，可支援農民與灌溉管理單位制定科學化的灌溉策略。

綜合上述成果，本研究提出數項重要結論與建議。首先，處理後城市污水可作為乾旱地區農業灌溉的可靠水源，特別是在供水有限或成本考量下，其與井水混用或搭配缺水灌溉的策略具良好適應性。其次，針對飼料玉米生產而言，應強化後期生育階段的水分管理，避免成熟期水分不足造成產量損失。第三，本研究所建立的三個生育期產量-用水函數與 Ky 係數，可作為氣候變異下作物灌溉計畫與水資源分配的決策工具。最後，為推動農業水資源永續利用，建議地方政府可推行處理後污水農用計畫，並搭配監測與水質管理機制，以確保農業環境安全與作物品質。

本研究以田間實證數據佐證城市污水再利用在農業系統中的多重效益，補足了乾旱地區作物需水反應研究中對非常規水源應用的不足。未來若能進一步結合經濟效益分析與風險評估，將有助於提升污水再利用策略的政策推動力與實務可行性，並促進作物生產與水資源管理的協同優化。

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Development of forage maize yield–water functions by applying simultaneous different levels of irrigation and treated municipal wastewater

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ABSTRACT

The aim of this study is to develop forage maize yield–water functions by applying different levels of irrigation and treated municipal wastewater. This research was conducted during May–August (2019 and 2020) in the field of the Marvdasht municipal wastewater treatment plant in a completely randomized block design with 12 treatments, 3 replications and 2 factors: (a) management of traditional deficit irrigation at 4 levels (full irrigation [FI] [100% irrigation requirement] and deficit irrigation at 40, 60 and 80% levels of water requirement); (b) use of wastewater at 3 levels (wastewater [WW], one-to-one mixture of well water and wastewater [50/50], and well water [W]).

Statistical models of evaluation were used to develop and evaluate yield–water functions and relative reduction in yield versus relative reduction in water consumption. The results of statistical evaluation of yield–water functions in three growth stages showed the relative advantage of yield–water functions of leaves in the vegetative stage, yield–water functions of stems in the flowering stage and yield–water functions of total dry matter in the grain-ripening stage compared to other functions.

The yield response factor (K_y) for total dry matter in the three stages of vegetative, flowering and ripening were 0.38, 0.52 and 0.63, respectively, and it was found that the most susceptible stage of maize growth to water deficiency was in the stage of grain ripening.

Analysis of the interactive effect showed that the highest values of total dry matter yield in the vegetative and flowering stages, and grain yield in the ripening stage were 7260, 9857 and 3158 kg ha⁻¹ in the WW-FI treatment (full irrigation with wastewater), while the lowest levels of yield were 5052, 6069 and 1508 kg ha⁻¹ in the W-DI60 treatment (60% deficit irrigation with well water). The results showed that the use of wastewater in traditional deficit irrigation conditions is beneficial for forage maize, so it can be recommended.

KEYWORDS

agriculture, deficit irrigation, forage maize, recycling, unconventional water, yield

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