

THE IMPACT OF ALTERNATE WETTING AND DRYING (AWD) ON METHANE EMISSIONS AND GROUNDWATER RECHARGE IN ORGANIC PADDY FIELDS

L'IMPACT DE L'ALTERNANCE D'HUMIDIFICATION ET D'ASSÈCHEMENT (AWD) SUR LES ÉMISSIONS DE MÉTHANE ET LA RECHARGE DES EAUX SOUTERRAINES DANS LES RIZIÈRES BIOLOGIQUES

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ABSTRACT

This study investigates the effects of conventional continuous flooding (CF) and alternate wetting and drying (AWD) irrigation management on methane emissions and groundwater recharge in organic paddy fields at the Taoyuan District Agricultural Research and Extension Station. Field observations indicate that AWD irrigation can effectively reduce methane emissions, with the annual methane emissions from the organic rotation field being significantly lower than those from the organic continuous cropping field. However, water balance analysis showed that the rotation field had a relatively higher percolation rate, suggesting that irrigation and cropping management practices may influence groundwater recharge processes. Since paddy fields are considered important groundwater recharge sources, it is necessary to evaluate whether water-saving irrigation practices may reduce regional groundwater recharge capacity.

To analyze the influence of agricultural irrigation on groundwater systems, this study applies the THMC (Thermo-Hydro-Mechanical-Chemical) model to establish a regional groundwater flow simulation system for the Taoyuan area. Compared with conventional groundwater models that mainly simulate saturated groundwater flow, the THMC model can simultaneously simulate water flow in both unsaturated and saturated zones, allowing more comprehensive representation of rainfall infiltration, irrigation recharge, and groundwater flow interactions. Geological drilling data, hydrogeological information, rainfall records, irrigation data, and groundwater observation data were integrated to construct a three-dimensional numerical groundwater model.

At the current stage, the steady-state simulation of the THMC groundwater model has been completed, and the preliminary results reasonably represent groundwater flow directions and groundwater level distributions in the Taoyuan area. Transient calibration is currently underway to improve the agreement between simulated and observed groundwater conditions. After calibration is completed, different irrigation scenarios, including CF and AWD, will be established to evaluate their effects on groundwater recharge and groundwater level variations.

Keywords: Alternate wetting and drying (AWD); Methane emissions; Paddy fields; Continuous flooding; Management practices.

RÉSUMÉ

Cette étude examine les effets de l'inondation continue conventionnelle (CF) et de la gestion de l'irrigation par alternance d'humidification et d'assèchement (AWD) sur les émissions de méthane et la recharge des eaux souterraines dans des rizières biologiques de la station de recherche et de

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vulgarisation agricoles du district de Taoyuan. Les observations de terrain indiquent que l'irrigation AWD peut réduire efficacement les émissions de méthane, les émissions annuelles de la parcelle biologique en rotation étant nettement inférieures à celles de la parcelle biologique en culture continue. Toutefois, l'analyse du bilan hydrique montre que la parcelle en rotation présente un taux de percolation relativement plus élevé, ce qui suggère que les pratiques de gestion de l'irrigation et des cultures peuvent influencer sur les processus de recharge des eaux souterraines. Les rizières étant considérées comme d'importantes sources de recharge des eaux souterraines, il convient d'évaluer si les pratiques d'irrigation économes en eau peuvent réduire la capacité régionale de recharge.

Pour analyser l'influence de l'irrigation agricole sur les systèmes d'eaux souterraines, cette étude applique le modèle THMC (thermo-hydro-mécanique-chimique) afin d'établir un système régional de simulation des écoulements souterrains dans la région de Taoyuan. Contrairement aux modèles classiques d'eaux souterraines qui simulent principalement les écoulements en zone saturée, le modèle THMC peut simuler simultanément les écoulements dans les zones non saturées et saturées, ce qui permet une représentation plus complète des interactions entre l'infiltration des précipitations, la recharge due à l'irrigation et l'écoulement des eaux souterraines. Les données de forage géologique, les informations hydrogéologiques, les relevés de précipitations, les données d'irrigation et les observations des eaux souterraines ont été intégrés pour construire un modèle numérique tridimensionnel des eaux souterraines.

À ce stade, la simulation en régime permanent du modèle THMC des eaux souterraines est achevée, et les résultats préliminaires représentent de manière satisfaisante les directions d'écoulement et la distribution des niveaux piézométriques dans la région de Taoyuan. L'étalonnage transitoire est en cours afin d'améliorer la concordance entre les conditions des eaux souterraines simulées et observées. Une fois l'étalonnage terminé, différents scénarios d'irrigation, notamment CF et AWD, seront établis afin d'évaluer leurs effets sur la recharge des eaux souterraines et les variations de leur niveau.

Mots clés : Alternance d'humidification et d'assèchement (AWD); Emissions de méthane; Rizières; Inondation continue; Pratiques de gestion.

INTRODUCTION

In recent years, global climate change has intensified, and the frequency of extreme droughts and heavy rainfall events has gradually increased, creating greater challenges for balancing water resource supply and demand. Although Taiwan receives higher annual rainfall than the global average, its steep terrain, short river systems, and uneven temporal and spatial rainfall distribution make rainfall difficult to retain effectively. Large amounts of rainfall often rapidly flow into the ocean within a short period of time. In contrast, prolonged drought periods frequently lead to insufficient surface water availability. As drought events have become increasingly frequent in recent years, groundwater has gradually become an important supplementary water source during dry seasons. Therefore, groundwater recharge and sustainable groundwater utilization have become important issues in regional water resource planning.

The agricultural sector is one of the major water users in Taiwan, and rice cultivation is a highly water-intensive agricultural activity. Conventional rice cultivation commonly adopts continuous flooding (CF), in which paddy fields remain inundated for extended periods during the growing season. This irrigation method helps stabilize crop yield and suppress weed growth; however, long-term flooding also creates oxygen-deficient soil conditions that activate methanogens and promote methane (CH₄) production. Methane is an important greenhouse gas with a global warming potential significantly higher than carbon dioxide. Therefore, paddy fields are considered one of the important agricultural sources of greenhouse gas emissions.

To reduce agricultural water demand and greenhouse gas emissions, alternate wetting and drying (AWD) irrigation management has been increasingly promoted in recent years. AWD alternates wet

and dry irrigation periods, temporarily restoring aerobic soil conditions and thereby reducing methane production. According to field experiments conducted in organic paddy fields at the Taoyuan District Agricultural Research and Extension Station, AWD can effectively reduce methane emissions. The annual methane emissions from the rotation field were significantly lower than those from the organic continuous cropping field, which remained flooded for extended periods. However, paddy fields not only function as agricultural production systems but may also serve as important groundwater recharge sources. When fields remain inundated for long periods, part of the irrigation water infiltrates through the soil and recharges the aquifer. Therefore, changes in irrigation management may affect not only methane emissions and irrigation water use, but also groundwater recharge and groundwater level variations.

The Taoyuan area has long been characterized by extensive agricultural irrigation, and its geological formations mainly consist of lateritic soil, lateritic gravel, and the Yangmei layer. The surface lateritic soil layer has relatively low permeability, whereas the underlying lateritic gravel layer possesses higher porosity and hydraulic conductivity and serves as the principal aquifer in the Taoyuan area. Since paddy field irrigation is closely related to groundwater level variation, establishing a regional-scale groundwater model to analyze the relationships among irrigation, rainfall infiltration, and groundwater recharge is significant.

Moreover, increasing industrial and domestic water demand in recent years has intensified water resource pressure in northern Taiwan. During drought periods, groundwater pumping often becomes an important supplementary water source. However, excessive groundwater extraction may lead to groundwater level decline and affect the long-term sustainability of groundwater resources. Accordingly, understanding groundwater recharge mechanisms is crucial for regional water resource management. In agricultural irrigation regions such as Taoyuan, paddy field irrigation may contribute significantly to groundwater recharge. Consequently, investigating the relationship between irrigation management and groundwater recharge is closely related not only to agricultural irrigation management but also to sustainable groundwater utilization.

Traditional groundwater studies have mainly focused on saturated groundwater flow. However, rainfall and irrigation water must first infiltrate through the unsaturated zone before recharging the aquifer. This process is influenced by soil properties, irrigation practices, infiltration conditions, and surface ponding duration. Consequently, models considering only saturated groundwater flow may not adequately describe groundwater recharge behavior. In contrast, the THMC model adopted in this study can simultaneously simulate water flow in both unsaturated and saturated zones, making it more suitable for evaluating groundwater recharge behavior under different irrigation management conditions.

Another important issue is the relationship between water-saving irrigation and groundwater recharge. Although AWD has the potential to reduce water irrigation and methane emissions, shortening the ponding duration in paddy fields may also reduce groundwater recharge. Because groundwater systems exhibit delayed responses, the impacts of groundwater recharge may not be immediately observable through short-term field observations alone. Hence, a regional-scale numerical groundwater model is required to further analyze the potential impacts of different irrigation management practices on groundwater systems.

RESEARCH METHOD

This study focuses on the Taoyuan area and applies the THMC model to establish a regional groundwater flow simulation system for investigating the influence of paddy field irrigation on the groundwater system. The main objective is to develop a THMC groundwater model applicable to groundwater management in the Taoyuan area and to analyze the effects of paddy field irrigation on groundwater levels. Compared with conventional groundwater models that mainly simulate saturated groundwater flow, the THMC model used in this study can simulate water flow in both unsaturated and

saturated zones. As a result, it can more comprehensively describe the interactions among rainfall infiltration, agricultural irrigation, and groundwater flow.

Since irrigation water applied to paddy fields must first infiltrate from the land surface and pass through the unsaturated zone before recharging the aquifer, water movement in the unsaturated zone plays a critical role in groundwater recharge. Models considering only saturated groundwater flow may not fully represent delayed infiltration and water storage processes in the unsaturated zone. In contrast, the THMC model can simultaneously simulate soil moisture variation and groundwater level dynamics, making it particularly suitable for agricultural regions with complex groundwater recharge behavior.

During model construction, geological and hydrogeological data from the Taoyuan area were first collected. Based on stratigraphic characteristics, the study area was conceptualized into several major geological layers, including the lateritic soil layer, lateritic gravel layer, and Yangmei layer. The surface lateritic soil layer has relatively low permeability, whereas the underlying lateritic gravel layer exhibits higher hydraulic conductivity and serves as the principal aquifer in the Taoyuan area. The Yangmei layer represents the deeper geological structure beneath the aquifer system.

For spatial discretization, geological drilling data and topographic data were used to construct the numerical grid. A two-dimensional triangular irregular network (TIN) was applied for horizontal discretization, followed by vertical stacking according to the depth and distribution of each geological layer to establish a three-dimensional groundwater numerical model representing the actual geological structure of the Taoyuan area.

The overall topography of the Taoyuan area gradually decreases from southeast to northwest, resulting in a distinct regional groundwater flow trend. Through the construction of a three-dimensional numerical grid, groundwater flow behavior among different geological layers and the spatial distribution of groundwater levels can be simulated. This model framework also serves as the basis for analyzing how rainfall and irrigation water are transported through subsurface media and subsequently affect groundwater levels.

In addition to geological structures, hydrogeological parameters were also assigned in the model, including hydraulic conductivity, porosity, and infiltration-related parameters. Since the permeability of the surface lateritic soil layer is lower than that of the underlying gravel layer, water movement through the unsaturated zone may exhibit significant delayed infiltration behavior. Accordingly, the capability of the THMC model to simulate unsaturated zone flow is particularly important in this study. Furthermore, significant differences in permeability exist among the geological layers in the Taoyuan area, meaning that groundwater recharge behavior may be strongly influenced by geological heterogeneity. The low-permeability lateritic soil layer near the surface may prolong water retention time, whereas the underlying lateritic gravel layer may form relatively rapid groundwater flow pathways. Through the construction of a three-dimensional groundwater model, this study can further analyze the spatial distribution characteristics of groundwater flow and groundwater recharge under different geological conditions.

For boundary condition settings, the coastal area on the northwestern side of the study area was assigned as a constant head boundary with a hydraulic head value of 0 m, while the remaining boundaries were set as no-flow boundaries. Surface recharge was simulated using variable boundary conditions. Unlike previous regional groundwater models that mainly considered rainfall infiltration, this study incorporated actual paddy field irrigation water as a dynamic surface recharge source through time-series variable boundary conditions. This approach enables the model to more realistically represent temporal variations in irrigation recharge and their influence on groundwater flow and groundwater level fluctuations. By integrating rainfall data with agricultural irrigation water balance characteristics, the model can simulate the dynamic vertical infiltration process of surface water through the unsaturated zone into the aquifer.

The incorporation of actual irrigation data is an important aspect of this study. Paddy field irrigation exhibits strong seasonal characteristics, and different cropping periods and irrigation management practices result in variations in irrigation amount and irrigation timing. Accordingly, irrigation data were processed as time-series recharge conditions to simulate groundwater level responses to irrigation events and compare the impacts of different irrigation management practices. In particular, differences between continuous flooding irrigation and alternate wetting and drying irrigation can be represented through adjustments in irrigation recharge amount and irrigation timing.

Besides irrigation data, rainfall data were also incorporated into the model as surface recharge conditions. Since rainfall intensity and rainfall duration strongly influence infiltration behavior, integrating rainfall hydrographs into the model is important for describing temporal variations in groundwater recharge. By combining rainfall recharge and irrigation recharge, the model can better represent groundwater level variations under actual hydrological conditions.

During steady-state model construction, observed groundwater levels from monitoring wells were used as constant head boundary conditions to establish the initial groundwater level distribution representing the actual groundwater environment in the Taoyuan area. Compared with constructing an initial groundwater level surface through spatial interpolation, directly using observed groundwater levels reduces errors caused by interpolation methods and uneven monitoring well distribution, thereby improving the reliability of the model initial conditions.

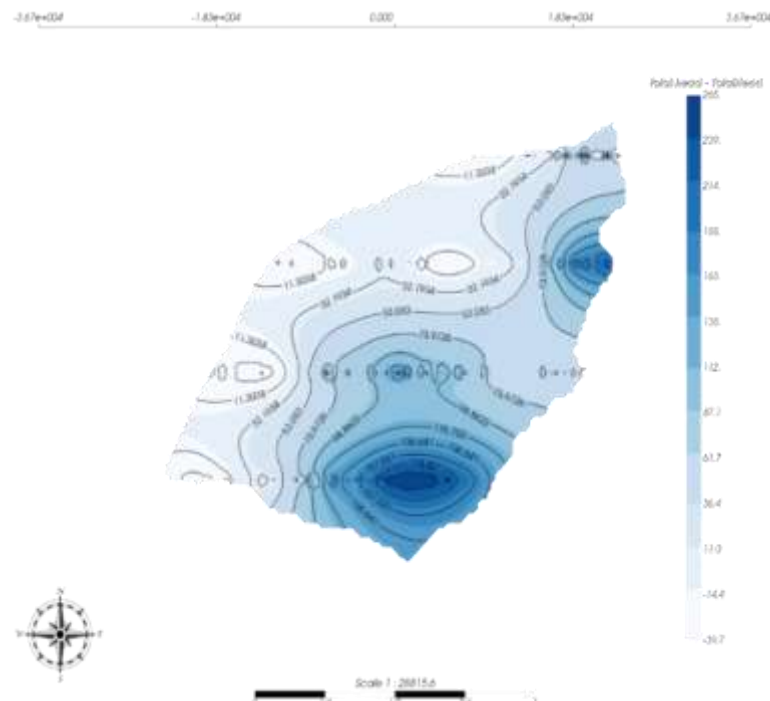
After the steady-state simulation was completed, the simulated groundwater levels were used as the initial groundwater level conditions for transient simulations to further analyze groundwater level dynamics over time. Current steady-state simulation results indicate that the simulated groundwater flow direction generally agrees with the actual groundwater flow trend in the Taoyuan area, with groundwater flowing from higher elevation regions toward the northwestern coastal area. This suggests that the geological framework and boundary condition settings of the model are reasonably established. Figure 1 shows the simulated groundwater head distribution under steady-state conditions in the Taoyuan area.

The ongoing transient calibration mainly focuses on adjusting groundwater level fluctuation magnitude, groundwater response timing, and regional groundwater flow trends. By comparing simulated groundwater levels with observed groundwater level time series, hydrogeological parameters can be gradually refined to improve model performance. Since groundwater systems exhibit delayed responses to rainfall and irrigation recharge, transient calibration is particularly important for model development.

To ensure that the model can realistically represent the spatial and temporal characteristics of groundwater in the Taoyuan area, transient calibration is currently ongoing.

Historical groundwater level records from monitoring wells within the study area are used as references during the calibration process. Hydraulic conductivity and porosity are adjusted to compare simulated groundwater levels with observed groundwater level variations over time.

After calibration is completed, groundwater level data from different periods will also be used for model validation to confirm model applicability and stability under varying temporal conditions. Root mean square error (RMSE) and coefficient of determination (R^2) will be adopted as statistical indicators for model performance evaluation. RMSE is used to quantify simulation error magnitude, whereas R^2 is used to evaluate the agreement between simulated groundwater level variations and observed trends. These indicators can further optimize model parameters and improve model reliability.



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