

DYNAMIC CONTROL OF SUBSURFACE DRAINAGE DURING WHEAT- GROWING PERIOD UNDER ROTATED RICE-WHEAT FIELD

CONTRÔLE DYNAMIQUE DU DRAINAGE SOUTERRAIN PENDANT LA PÉRIODE DE CROISSANCE DU BLÉ DANS UN CHAMP DE RIZ-BLÉ EN ROTATION

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ABSTRACT

Rice-wheat rotation is a main agricultural production system in the Yangtze River Basin of China. To better improve subsurface drainage management in rice-wheat rotation field, the control height of subsurface drainage is a crucial parameter. The setting of the control height needs to fully consider multiple objectives of crop requirements, waterlogging disasters, and drainage pollution. This paper proposes a multi-objective optimization method using HYDRUS-2D coupled with Strength Pareto Evolutionary Algorithm 2 (SPEA2). Dynamic drainage control heights were investigated across ten representative years, including three dry, three normal, three wet, and one extremely wet year. Taking the case of subsurface drainage in Gaoyou Irrigation District as example, dynamic control heights of subsurface drainage for ten representative years among 1956–2017 were studied. The results indicated that the determination of control height for subsurface drainage is influenced by the hydrological year type, as well as by rainfall conditions during each growth stage. In wet years, the controlled drainage height during the paddy drying period is set to 0 cm; for wheat, the control heights during the sowing and emergence stage, tillering stage, jointing stage, booting and heading stage, milking stage, and yellow ripening stage are set to 46 cm, 43 cm, 37 cm, 0 cm, 49 cm, and 23 cm, respectively. In normal years, the controlled drainage height during the paddy drying period is set to 38 cm; for wheat, the control heights are set to 50 cm, 42 cm, 20 cm, 41 cm, 43 cm, and 37 cm in sequence, respectively. In dry years, the controlled drainage height during the paddy drying period is set to 7 cm; for wheat, the control heights are set to 46 cm, 13 cm, 34 cm, 40 cm, 5 cm, and 14 cm in sequence.

Keywords: Rice- wheat rotation; agricultural production system; controlled drainage; subsurface drainage; paddy drying period.

RESUME

La rotation riz-blé est l'un des principaux systèmes de production agricole dans le bassin versant de Yangtze en Chine. Pour optimiser la gestion du drainage souterrain dans les parcelles pratiquant cette rotation, la hauteur de contrôle du drainage est un paramètre crucial. Le réglage de la hauteur de contrôle doit pleinement prendre en compte les multiples objectifs liés aux besoins des cultures, aux catastrophes liées à l'engorgement et à la pollution du drainage. Cet article propose une méthode d'optimisation à objectifs multiples utilisant HYDRUS-2D couplée à l'algorithme évolutif de Pareto fort 2 (SPEA2). Les hauteurs de contrôle du drainage dynamique ont été étudiées sur dix années représentatives, dont trois années sèches, trois normales, trois humides et une extrêmement humide. En tenant en compte le cas du drainage souterrain du périmètre irrigué de Gaoyou comme exemple, on a étudié les hauteurs de contrôle dynamiques du drainage souterrain pendant dix années représentatives entre la période 1956 et 2017. Les résultats indiquent que la détermination de la hauteur de contrôle du drainage souterrain dépend du type d'année hydrologique ainsi que des conditions pluviométriques à chaque stade de développement. Lors des années humides, la hauteur de drainage contrôlée durant la période de séchage du paddy est fixée à 0 cm; pour le blé, les hauteurs de contrôle

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durant la période de semis-levée, de tallage, de tige articulée, d'ébauchage et d'étêtage, de stade laiteux et de jaunissement sont fixées à 46 cm, 43 cm, 37 cm, 0 cm, 49 cm et 23 cm respectivement. Dans les années normales, la hauteur de drainage contrôlée pendant la période de séchage du paddy est fixée à 38 cm; pour le blé, les hauteurs de contrôle sont fixées successivement à 50 cm, 42 cm, 20 cm, 41 cm, 43 cm et 37 cm en séquence, respectivement. Pendant les années sèches, la hauteur de drainage contrôlée pendant la période de séchage du paddy est fixée à 7 cm; pour le blé, les hauteurs de contrôle sont fixées successivement à 46 cm, 13 cm, 34 cm, 40 cm, 5 cm et 14 cm.

Mots-clés : Rotation riz-blé; Système de production agricole; Drainage contrôlé; Drainage souterrain; Période de séchage du paddy.

1. Introduction

Rice-wheat rotation is a main agricultural production system in the Yangtze River Basin of China. Climate change is increasingly affecting water resources and irrigation in the rice-wheat rotation areas. Specifically, drought intensity during the wheat-growing season shows an upward trend, and at the same time waterlogging disaster is also prone to occur during the wheat period. Subsurface drainage is a common approach for managing waterlogging, particularly for subsurface waterlogging, which is more manageable (Christen *et al.*, 2001; Ritzema *et al.*, 2008).

Crop growth is a complex physiological process in which every element contributes to the formation of final yield. Therefore, controlled drainage should be dynamically adjusted, and the drainage control height should also vary correspondingly throughout the growth period. Determining the control height of subsurface drainage represents a critical multi-objective optimization challenge, as it must simultaneously achieve three key objectives: (1) preventing waterlogging stress that can damage crops; (2) avoiding excessive drainage that may lead to drought stress and reduce irrigation demand; and (3) facilitating water environmental protection and pollution control through regulated effluent management.

The approach of coupling simulation models with external optimization algorithms, also referred to as model-based optimization, has been widely applied across various water-related studies (Reed *et al.*, 2013; Maier *et al.*, 2014). Jonoski *et al.* (2019) evaluated the operation of flood storage areas in the Huai River by coupling HEC-RAS with global optimization algorithms, including NSGA-II, PESA-II, and SPEA-II. The HYDRUS model has been extensively applied to simulate water table dynamics, drainage discharge, and solute transport in subsurface drainage systems (Salehi *et al.*, 2016; Tao *et al.*, 2017; Tao *et al.*, 2021; Liu *et al.*, 2025). However, current research using HYDRUS predominantly focuses on analyzing soil-water-solute dynamics under various scenarios, yet it has been rarely employed in optimization studies—particularly in the case of HYDRUS-2D.

The main objective of this study is to propose an optimized control height for subsurface drainage during the wheat-growing season in rice-wheat rotation systems by coupling HYDRUS with the optimization algorithm SPEA2. Dynamic drainage control heights were investigated across representative years. This study contributes to advancing the integration of commercial simulation software with optimization algorithms and supports improved agricultural drainage management practices.

2. Materials and methods

2.1 Multi-objective function

The control height of subsurface drainage directly regulates groundwater depth, drainage discharge, and soil evaporation rates, thereby substantially influencing crop yield formation. The objectives of dynamically controlling subsurface drainage during the wheat-growing period are to maximize yield and minimize drainage discharge.

(1) Based on evapotranspiration

The mathematical relationship between relative yield and relative evapotranspiration was established by Jensen (1968) is as follows:

$$\frac{Y_a}{Y_m} = \prod_{i=1}^N \left(\frac{ETa_i}{ETc_i} \right)^{\lambda_i} \quad (1)$$

Where Y_a is the actual harvested yield, Y_m is the maximum crop yield under given management conditions that can be obtained when water is not limiting, N is the number of growth stages, ETa_i is the actual evapotranspiration and ETc_i is evapotranspiration for non-limiting water conditions during the i th stage of growth and λ_i is the sensitivity index of crop to water stress during the i th stage of growth.

(2) Based on waterlogging

Wu *et al.* (2017) developed a yield model for winter wheat based on SEW_{50} and suggested that a critical groundwater depth of 50 cm is suitable for wheat cultivation in the Jiangnan Plain, China. Furthermore, Kahlown *et al.* (2005) determined that a groundwater table depth of 50 cm represents a critical threshold at which wheat can meet its entire water requirement from groundwater.. Hence, SEW_{50} was selected as the indicator to reflect waterlogging intensity in this study.

$$SEW_{50} = \sum_{i=1}^t (50 - ht_i) \quad \text{when } ht_i > 50, ht_i = 50 \quad (2)$$

Where t is the total time, ht_i is the groundwater table depth at the i th day.

(3) Based on pollution reduction and water resources saving

A lower drainage volume generally indicates reduced pollutant export and decreased consumption of water resources. The total drainage volume can be calculated using the following equation:

$$TDrain = \sum_{i=1}^t drain_i \quad (3)$$

Where $TDrain$ is the total drainage volume, $drain_i$ is the drainage volume at the i th day.

2.2 Framework of HYDRUS-2D coupled with optimization algorithms

The model-based optimization framework consists of two main components. The first involves the development of a subsurface drainage simulation model using HYDRUS-2D, from which key variables including actual evaporation, water head, groundwater table depth, and drainage volume are obtained. The soil moisture state at the end of each growth stage serves as the initial condition for the subsequent stage, and this process is repeated until all stages are simulated. The second component is the optimization process, which utilizes an external algorithm to handle three objectives requiring maximization or minimization. Upon completion of the optimization process, a set of nondominated solutions is obtained.

2.3 Case study

Gaoyou Irrigation District located in the Yangtze River Basin of China; it features flat terrain. It is a typical gravity-fed plain canal irrigation district in southern China. Rice-wheat rotation is a main agricultural production system. The district has a north subtropical humid monsoon climate vulnerable to floods and droughts. The annual average temperature is 15°C, with extreme maximum and minimum temperatures of 38.5°C and -18.5°C respectively. Annual average sunshine hours total 2239, average relative humidity is 67%, multi-year average precipitation is 1018 mm, evaporation capacity is 1060 mm. Influenced by ocean monsoons, rainfall is unevenly distributed. Precipitation from June to July accounts for around 60% of the annual total, corresponding to the plum rain season. Typhoon-triggered rainstorms frequently

occur in August. Local agriculture adopts double cropping of rice and wheat, and agricultural water consumption accounts for approximately 70% of the total water use.

Based on the water requirements of wheat at different phenological stages and with reference to relevant literature (Yuan et al., 2016), the wheat growth period is divided into six stages: sowing to seedling, seedling to tillering, tillering to stem elongation, stem elongation to heading and grain filling, heading and grain filling to milk ripening, and milk ripening to yellow ripening. Details are provided in Table 1.

Table 1. Details of the parameters of growing stage

Crop	Growth stage	Abbreviation	Date
Rice	Maturity period	RM	26 Sep.-16 Oct.
	Fallow period		
Wheat	Sowing-Seeding stage	WSS	17 Oct.-23 Oct.
	Seeding-Tillering stage	WST	24 Oct.-19 Nov.
	Tillering-Elongation stage	WTE	20 Nov.-18 Mar.
	Elongation-Heading & grain filling stage	WEHF	19 Mar.-8 Apr.
	Heading & grain filling -Milk Ripeness stage	WHFMR	9 Apr.-30 Apr.
	Milk Ripeness -Yellow Ripeness stage	WMRYR	1 May-23 May

The control height of subsurface drainage is primarily influenced by rainfall. Rainfall data during the control period from 1956 to 2017 were analyzed. The rainfall distribution across different growth periods is presented in Figure 1. The drain spacing of subsurface drainage is 20m and the drain depth is 1m. Soil hydraulic parameters were adopted from Tao et al. (2025). The drain boundary was defined as a seepage face boundary under pressure, where the pressure value corresponds to the control height and was updated in each simulation. The initial soil condition was set as saturated, reflecting the rice maturity period, with no ponding water allowed at the surface. Based on the simulation setup and growth stage division, the sensitivity index of the crop to water stress during each wheat growth stage of WSS, WST, WEHF, WHFMR, WMRYR are 0.1721, 0.05, 0.1694, 0.3108, 0.1895 and 0.1895.

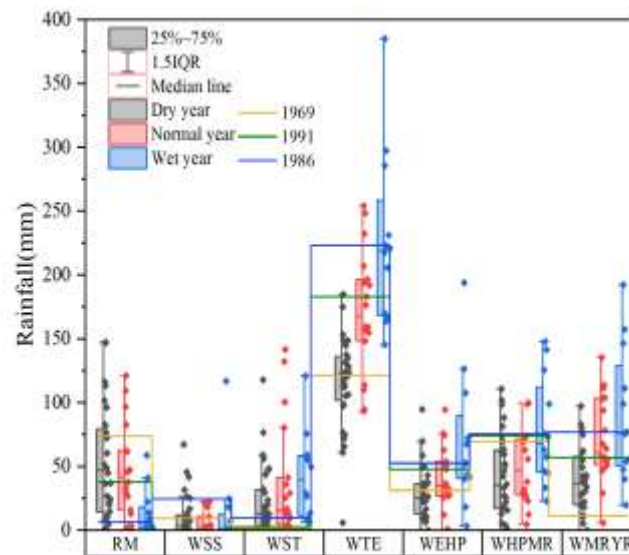


Figure 1. Rainfall in different growth stages

3. Results and discussion

3.1 Control height in wet year

The hypervolume indicator was employed to evaluate the reliability of the optimization results, and all subsequent data represent validated outcomes. In the wet year (1986), crop yield experienced almost no reduction due to drought stress; thus, the optimization primarily involved a trade-off between Objective Function 2 and Objective Function 3. Figure 2 displays the values of these two objective functions under the Pareto solution set.

As shown, when waterlogging is completely prevented ($SEW_{50}=0\text{cm}$), the corresponding drainage volume is 24013 cm^2 . In contrast, when drainage volume is minimized, SEW_{50} reaches 17 cm , and the drainage volume is 26% lower than that case of $SEW_{50}=0\text{cm}$.

If no constraints are imposed on the expected values of waterlogging and drainage volume, and all solutions are considered feasible, the distribution of optimal solutions across the entire Pareto set can be observed in Figure 3. Overall, the median control heights during the RM, WSS, WEHF growth stages are relatively consistent, whereas greater variability is observed in the WST and WTE stages. If median values are adopted for regulation, in wet years, the controlled drainage height during the paddy drying period is set to 0 cm ; for wheat, the control heights during the sowing and emergence stage, tillering stage, jointing stage, booting and heading stage, milking stage, and yellow ripening stage are set to 46 cm , 43 cm , 37 cm , 0 cm , 49 cm , and 23 cm , respectively.

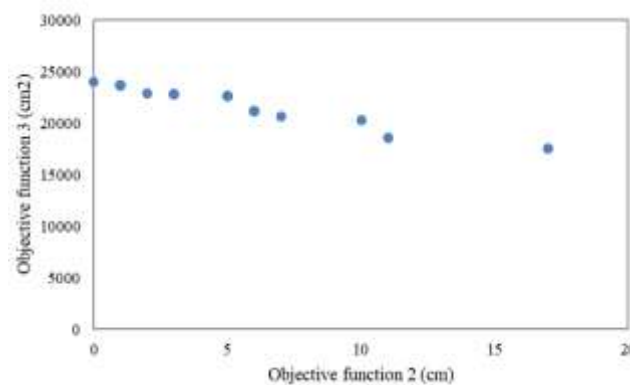


Figure 2. Objective functions values of the optimal solutions in 1986

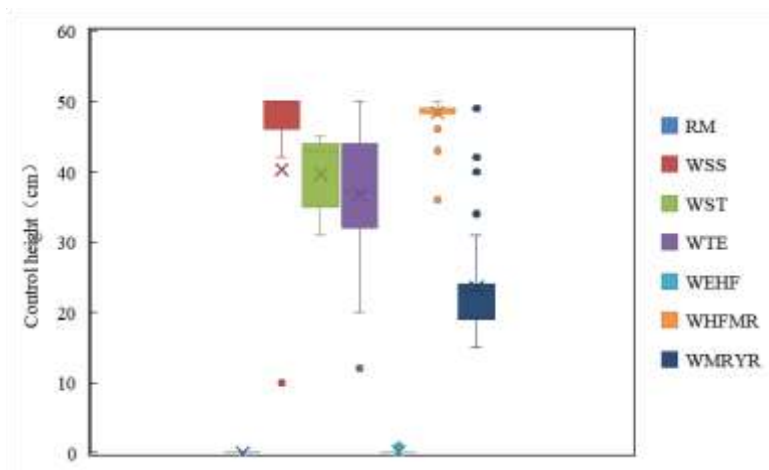


Figure 3. Pareto set of optimal solutions in 1986

3.2 Control height in normal year

In normal years, rational subsurface drainage control can control evaporation without yield loss and minimize waterlogging damage. A zero SEW_{50} value indicates negligible impacts on crop growth. Meanwhile, drainage volume can be minimized via regulated drainage, achieving optimization of the three objectives. The

All solutions are considered feasible, the distribution of optimal solutions across the entire Pareto set can be observed in Figure 4. Overall, the median control heights during the RM, WSS, WST, WTE, WMRYR growth stages are relatively consistent, whereas greater variability is observed in the WEHF and WHFMR stages. If median values are adopted for regulation, in normal years, the controlled drainage height during the paddy drying period is set to 38 cm; for wheat, the control heights during the sowing and emergence stage, tillering stage, jointing stage, booting and heading stage, milking stage, and yellow ripening stage are set to 50 cm, 42 cm, 20 cm, 41 cm, 43 cm, and 37 cm in sequence, respectively.

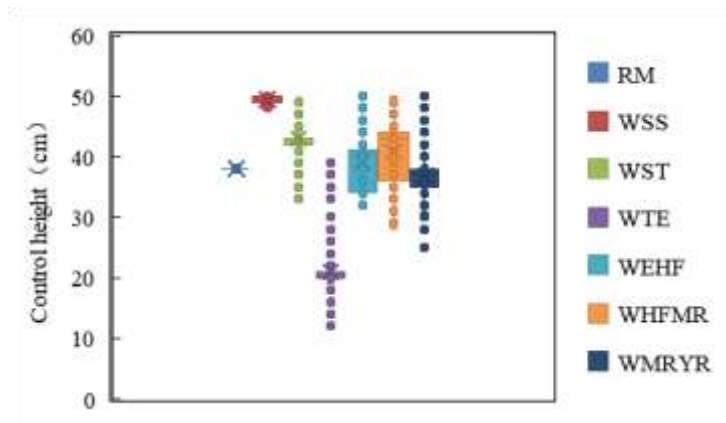


Figure 4. Pareto set of optimal solutions in 1991

3.4 Control height in dry year

In dry years, subsurface drainage control can achieve optimization of the three objectives. All solutions are considered feasible, the distribution of optimal solutions across the entire Pareto set can be observed in Figure 5. If median values are adopted for regulation, in dry years, the controlled drainage height during the paddy drying period is set to 7 cm; for wheat, the control heights during the sowing and emergence stage, tillering stage, jointing stage, booting and heading stage, milking stage, and yellow ripening stage are set to 46 cm, 13 cm, 34 cm, 40 cm, 5 cm, and 14 cm in sequence, respectively.

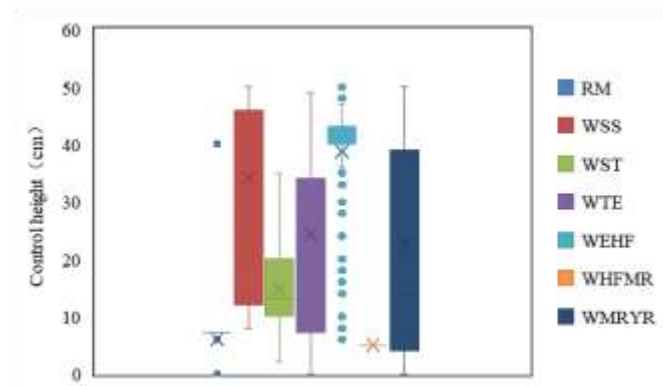


Figure 5. Pareto set of optimal solutions in 1969

4. Conclusion

HYDRUS was coupled with the Strength Pareto Evolutionary Algorithm 2 (SPEA2) to determine optimal subsurface drainage control heights for wheat cultivation in a rice-wheat rotation system, considering multiple objectives.

The main conclusions are as follows: In wet years, the controlled drainage height during the paddy drying period is set to 0 cm; for wheat, the control heights during the sowing and emergence stage, tillering stage, jointing stage, booting and heading stage, milking stage, and yellow ripening stage are set to 46 cm, 43 cm, 37 cm, 0 cm, 49 cm, and 23 cm, respectively. In normal years, the controlled drainage height during the paddy drying period is set to 38 cm; for wheat, the control heights are set to 50 cm, 42 cm, 20 cm, 41 cm, 43 cm, and 37 cm in sequence, respectively. In dry years, the controlled drainage height during the paddy drying period is set to 7 cm; for wheat, the control heights are set to 46 cm, 13 cm, 34 cm, 40 cm, 5 cm, and 14 cm in sequence.

Rainfall distribution varies across crop growth stages in different hydrological years. Further research shall be conducted on control strategies for diverse scenarios in the future.

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