

INTEGRATED MODELING OF FIELD DRAINAGE AND ENGINEERING SCHEDULING FOR PLAIN RIVER NETWORK IRRIGATION DISTRICTS IN SOUTHERN CHINA

MODÉLISATION INTÉGRÉE DU DRAINAGE DES CHAMPS ET DE LA PROGRAMMATION DU GENIE POUR LES PERIMETRES IRRIGUES DU RÉSEAU FLUVIAL PLAT AU SUD DE LA CHINE

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ABSTRACT

Plain river network irrigation districts in southern China are characterized by flat terrain, dense and interwoven channels, weak natural drainage gradients, and intensive drainage infrastructure, making them highly vulnerable to waterlogging during plum-rain and typhoon rainfall. To analyze drainage processes under different storm conditions and evaluate the effects of hydraulic-structure scheduling, this study develops a coupled drainage simulation and scheduling model for plain river network irrigation districts. The model consists of four modules: a Xin'anjiang rainfall-runoff module, a conceptual pond module representing minor ditches, field canals, and pond bodies as lumped internal storage, a one-dimensional Saint-Venant hydrodynamic module for the backbone river network, and a rule-based scheduling module for sluice gates and pumping stations. The model was applied to the Shangtanghe Irrigation District in Zhejiang Province, China, which covers 206.5 km² and includes 30 main channels, 24 sluice gates, and 11 pumping stations. Calibration and validation against observed rainfall events produced district-wide Nash–Sutcliffe efficiencies of 0.997 and 0.988, respectively, with all 11 monitoring stations achieving NSE values no lower than 0.881. Scenario analysis across 16 design and historical rainfall cases shows that storage–discharge balance scheduling reduced reach exceedance ratios by up to 25 percentage points compared with regulation-based scheduling, while peak water-level reductions were generally within 0.05 m in design storms. For a 14-day plum-rain sequence, exceedance duration decreased from 86.0 to 49.2 h. Further optimization indicates that lowering control water levels and increasing pumping capacity act on different drainage phases and provide complementary benefits when combined. The results demonstrate that coupled hydrological-hydraulic simulation with dynamic structure scheduling can support drainage strategy assessment and improvement planning in lowland irrigation districts.

Keywords: irrigation districts; sluice gates; pumping stations; water levels; drainage strategy assessment.

RESUME

Les périmètres irrigués du réseau fluvial plat situés au sud de la Chine sont caractérisés par un terrain plat, des canaux denses et entrelacés, des gradients de drainage naturels faibles et une infrastructure de drainage intensive, ce qui les rend très vulnérables à l'engorgement lors des précipitations liées à la mousson asiatique orientale (pluies de la prune) et des précipitations durant les typhons. Pour analyser les processus de drainage sous différentes conditions de tempête et évaluer les effets de la programmation des ouvrages hydrauliques, cette étude développe un modèle couplé de simulation et de programmation du drainage pour les périmètres irrigués du réseau fluvial plat. Le modèle se

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compose de quatre modules : un module de l'écoulement naturel de type Xin'anjiang; un module conceptuel d'étangs représentant des fossés mineurs, des canaux de champs et des corps d'étangs en tant que stockage interne groupé; un module hydrodynamique unidimensionnel de Saint-Venant pour le réseau fluvial principal; et un module de programmation basé sur des règles pour les vannes d'écluse et les stations de pompage. Le modèle a été appliqué au périmètre irrigué de Shangtanghe dans la province du Zhejiang, en Chine, qui couvre une superficie de 206,5 km² et comprend 30 canaux principaux, 24 vannes et 11 stations de pompage. La calibration et la validation par rapport aux événements de précipitations observés ont produit des efficacités Nash–Sutcliffe à l'échelle du périmètre de 0,997 et 0,988, respectivement, les 11 stations de surveillance ayant toutes atteint des valeurs NSE supérieures ou égales à 0,881. L'analyse des scénarios sur 16 cas de précipitations nominales et historiques montre que la programmation de l'équilibre entre stockage et débit a permis de réduire les taux de dépassement des niveaux critiques dans les biefs jusqu'à 25 points de pourcentage par rapport à la programmation basée sur la réglementation, tandis que les réductions maximales des niveaux d'eau étaient généralement inférieures à 0,05 m lors des averses nominales. Pour un épisode de «pluies de la prune» d'une durée de 14 jours, la durée de dépassement des seuils critiques est passée de 86,0 à 49,2 heures. Une optimisation complémentaire indique que l'abaissement des niveaux d'eau de contrôle et l'augmentation de la capacité de pompage agissent sur des phases différentes du drainage et offrent des avantages complémentaires lorsqu'ils sont combinés. Les résultats démontrent que la simulation hydrologique-hydraulique couplée à la programmation dynamique des ouvrages peut soutenir l'évaluation de la stratégie de drainage et la planification de l'amélioration dans les périmètres irrigués de basse terre.

Mots-clés : Périmètres irrigués; Vannes d'écluse; Stations de pompage; Niveaux d'eau; Evaluation de la stratégie de drainage.

INTRODUCTION

Plain river network irrigation districts are highly vulnerable to waterlogging because their drainage response is governed by flat topography, small hydraulic gradients, dense artificial channels, and the coordinated operation of sluice gates and pumping stations (Tang et al., 2023). In these districts, heavy rainfall can rapidly produce excess field water, while backwater interactions and bidirectional flows within the channel network may redistribute flood exposure among sub-areas (Shang et al., 2025; Li et al., 2026). Increasing rainfall extremes have therefore raised the need for simulation tools that can represent coupled hydrological and hydraulic processes and evaluate alternative drainage operation strategies under multiple storm conditions (Li et al., 2026). Hydrological rainfall-runoff models and one-dimensional hydrodynamic models have been widely coupled for flood and drainage simulation in lowland basins (Waseem et al., 2020; Zhang et al., 2025). Related studies in flat agricultural districts have also combined paddy-field or sub-district water balance models with ditch-river hydrodynamic solvers and achieved reasonable water-level simulations (Chen et al., 2020; Xiong et al., 2021; Liu et al., 2021). However, two issues remain important for district-scale applications in plain river networks. First, runoff from inter-channel areas is often connected directly to the backbone river network, whereas minor ditches, field canals, and ponds provide intermediate storage, delayed drainage, and indirect hydraulic connectivity (Shen et al., 2021; Tang et al., 2022). Second, sluice gates and pumps are frequently prescribed as fixed boundary conditions rather than adjusted according to simulated water levels, limiting the assessment of alternative scheduling strategies (Liu et al., 2021; Meng et al., 2025).

This study develops an integrated coupled model for drainage performance assessment in plain river network irrigation districts. The model links rainfall-runoff generation, internal drainage storage, river-network hydrodynamics, and rule-based structure scheduling within one simulation framework. A conceptual pond is used to represent the minor ditches, field canals, and pond bodies within each inter-channel block as a lumped storage unit. This treatment preserves the main buffering and indirect connectivity effects of the internal drainage network without explicitly resolving all small channels. The scheduling module updates gate and pump operation from simulated water levels, allowing different operation rules to be compared under identical rainfall and boundary conditions.

The model is applied to the Shangtanghe Irrigation District in Zhejiang Province, China. After calibration and validation against observed rainfall events, two scheduling strategies are compared under design and historical storm scenarios, and additional optimization measures involving control water levels and pumping capacity are evaluated. Through this case study, the paper demonstrates how a coupled hydrological-hydraulic and scheduling model can support drainage strategy comparison and improvement planning in plain river network irrigation districts.

STUDY AREA AND MODEL FRAMEWORK

Study area and data

The Shangtanghe Irrigation District is located in Haining City, Zhejiang Province, eastern China, within the Hangjiahu Plain of the Yangtze River Delta (Fig. 1). The district covers approximately 206.5 km² and consists of two hydraulically independent subdistricts: a western sub-district of 145.5 km² and an eastern sub-district of 61.0 km². It is a typical lowland river network irrigation district, with flat terrain, dense channels, seasonal monsoon and typhoon rainfall, and drainage controlled mainly by sluice gates, pumps, and overflow weirs. These conditions make the drainage response sensitive not only to rainfall magnitude, but also to channel connectivity, backwater effects, and structure operation.

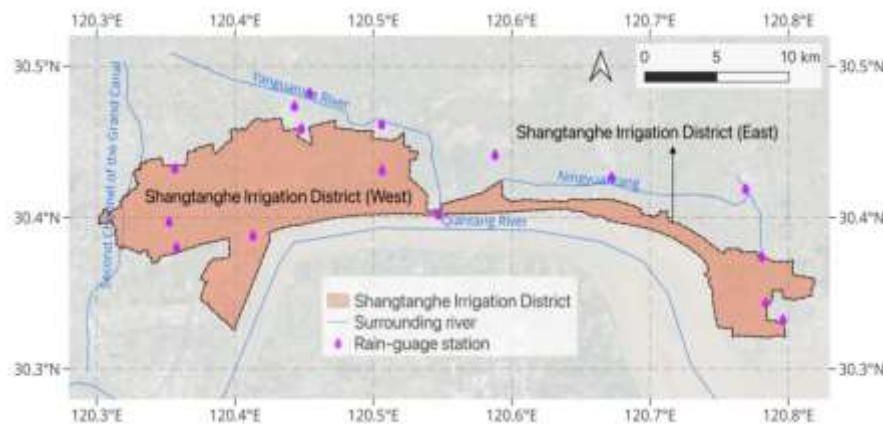


Figure 1. Location of the Shangtanghe Irrigation District within Haining City, Zhejiang Province, China, showing the West and East sub-districts, surrounding rivers, and rainfall monitoring stations.

The main drainage network contains 30 channels with a total length of 173 km and 40 junction nodes. Between the backbone channels, minor ditches, field canals, and pond bodies form an internal drainage network with an aggregate water surface area of approximately 12.75 km², or 6.2% of the district area. This internal network provides important storage and delayed drainage before runoff enters the backbone channels. Hydraulic exchange with the external canal system is controlled by 24 sluice gates, 11 pumping stations, and 13 overflow weirs, among which the boundary structures serve as the main drainage outlets and scheduling objects.

Model inputs and evaluation data included surveyed channel cross-sections, a DEM, land-use and paddy-field maps, hydraulic structure parameters, and operational records of gate and pump scheduling. Rainfall inputs were obtained from 16 rain-gauge stations within and around the district. Water-level observations at 11 monitoring stations were used for calibration and validation. A moderate rainfall event in January 2023 was selected for calibration, and an intense plum-rain event in June 2023 was used for validation, providing two contrasting tests of the model under different rainfall and antecedent conditions.

Coupled model framework

The model couple's rainfall-runoff generation, internal drainage storage, one-dimensional river-network hydrodynamics, and rule-based structure scheduling (Fig. 2).

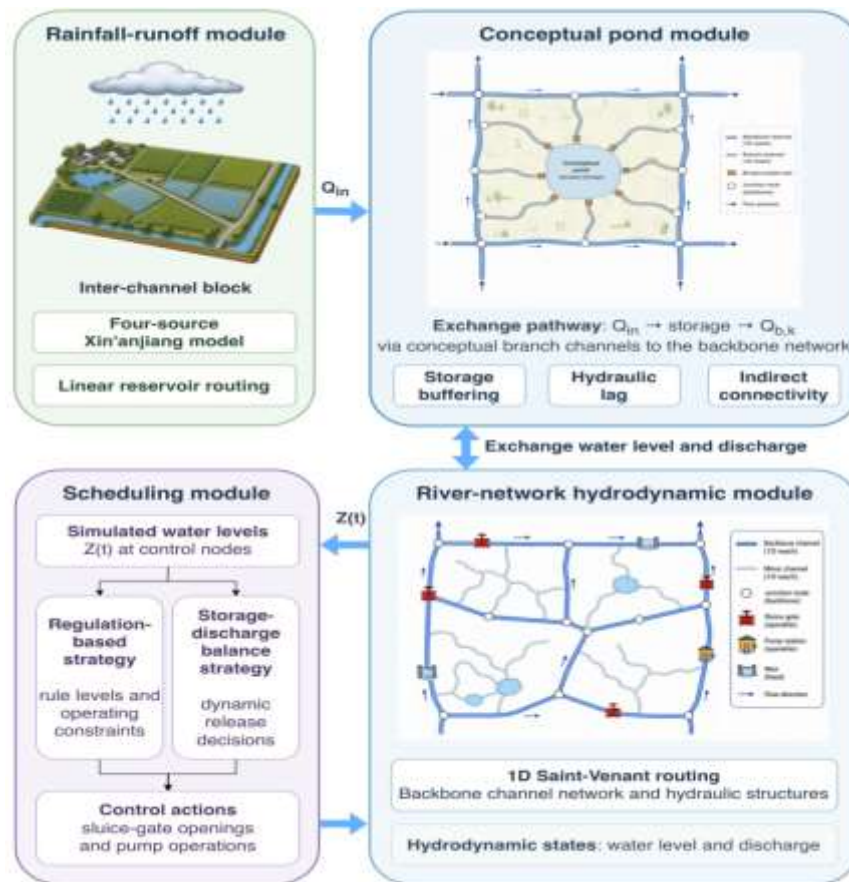


Figure 2. Schematic overview of the coupled model framework. Runoff from each inter-channel block enters a conceptual pond, exchanges with the backbone channel network through conceptual branch channels, and is affected by structure-operation decisions issued by the scheduling module.

The rainfall-runoff module uses the four-source Xin'anjiang model (Zhao, 1992) to convert areal rainfall over each inter-channel block into surface runoff, interflow, and shallow and deep groundwater contributions. These runoff components are routed to the internal drainage storage associated with each block. The conceptual pond module represents the minor ditches, field canals, and pond bodies within each inter-channel block as a lumped storage unit. Runoff first enters the conceptual pond and then exchanges with adjacent backbone channels through conceptual branch channels. This treatment retains the buffering and delayed-drainage effect of the internal network without resolving individual small channels.

The backbone channel network is solved with a one-dimensional Saint-Venant hydrodynamic model, which represents unsteady flow, backwater interactions, and flow reversals in the flat river network. Surveyed cross-sections provide the geometric basis for the solver, and additional computational sections are generated from water-level–area, water-level–width, and water-level–hydraulic-radius look-up relationships. Sluice gates, overflow weirs, and pumping stations are embedded as controllable internal or boundary conditions, so that changes in structure operation directly modify the simulated flow field.

The scheduling module is embedded in the hydrodynamic simulation loop. At each scheduling interval, simulated water levels are read from selected control stations and converted into gate openings or pump discharges for the key boundary structures. Two scheduling strategies are compared in this study. The regulation-based strategy follows the existing operating protocols, in which structure settings are determined from water-level thresholds. The storage–discharge balance strategy estimates the net

inflow to each sub-district and allocates drainage capacity to match that inflow more directly. Because both strategies are executed in the same coupled model, their performance differences can be attributed to the scheduling logic rather than to changes in rainfall, boundary conditions, or hydraulic representation.

MODEL CALIBRATION AND VALIDATION

Model configuration and calibration

The model domain was divided into 26 inter-channel blocks, including 22 in the western sub-district and 4 in the eastern sub-district. Each block was assigned one conceptual pond, and the backbone river network was represented by 902 computational crosssections along 30 channels with a total length of 173 km and 40 junction nodes. The hydrodynamic solver used a 10 s time step, and the scheduling module was invoked every 1 h. A total of 169 conceptual branch channels connected the conceptual ponds to adjacent backbone-channel junctions, and all surveyed sluice gates, pumping stations, and overflow weirs were included as hydraulic control structures.

Two rainfall-drainage events with complete water-level observations at all 11 monitoring stations were used. The calibration event, from 12 to 15 January 2023, was a moderate winter storm with rainfall totals of 42.0 mm in the western sub-district and 24.5 mm in the eastern sub-district. The validation event, from 23 to 26 June 2023, was an intense plum-rain episode with nearly uniform rainfall totals of 93.9 and 94.0 mm in the western and eastern sub-districts, respectively. The validation event was therefore substantially wetter and more intense than the calibration event, providing an independent test of parameter transferability.

Calibration was performed by adjusting three parameter groups: the Xin'anjiang rainfall-runoff parameters, Manning's roughness coefficients for different channel categories, and the conceptual pond area assigned to each inter-channel block. The final calibrated parameter set was then kept unchanged for the validation event; only rainfall inputs, initial conditions, and recorded structure-operation sequences were updated. Model performance was evaluated using NSE, RMSE, MAE, relative peak water-level error, and time-to-peak error. District-wide composite values were computed by pooling the simulated and observed water-level series from all 11 monitoring stations.

Validation performance

The pooled scatter plots (Fig. 3) show that simulated water levels closely match observations in both events, with points clustered around the 1:1 line and no evident systematic bias across the observed water-level range.

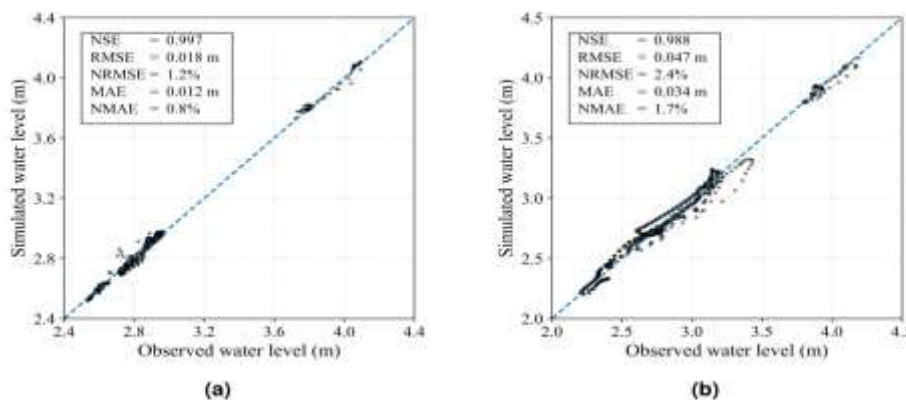


Figure 3. Simulated versus observed water levels at all 11 monitoring stations, pooled across all time steps, for (a) the calibration event and (b) the validation event. The dashed line is the 1:1 reference.

Table 1. Summary of calibration and validation performance.

Event	NSE	RMSE (m)	MAE (m)	Station NSE range	Peak error range (%)	Peak timing error (h)
Calibration	0.997	0.018	0.012	0.885-0.982	0.0-10.7	within ± 1.7
Validation	0.988	0.047	0.034	0.881-0.963	1.0-14.1	within ± 3.2

For the calibration event, the district-wide composite NSE was 0.997, with RMSE of 0.018 m and MAE of 0.012 m (Table 1). Station-level NSE values ranged from 0.885 to 0.982, and time-to-peak errors were within ± 1.7 h at all stations. For the validation event, the same calibrated parameter set produced a district-wide NSE of 0.988, RMSE of 0.047 m, and MAE of 0.034 m, despite the much stronger rainfall. All 11 monitoring stations achieved $\text{NSE} \geq 0.881$; six exceeded 0.920. Peak water-level errors were generally within 11%, with one station reaching 14.1%, and time-to-peak errors did not exceed ± 3.2 h. These results indicate that the coupled model reproduces the observed water-level dynamics of the plain river network irrigation district under rainfall conditions of contrasting intensity and spatial distribution. The validation event was simulated without recalibrating model parameters, so the consistently high performance supports the use of the model for the subsequent scheduling scenario analysis.

SCENARIO ANALYSIS

Scenario design

Sixteen rainfall scenarios were constructed to evaluate drainage performance under both design and historical rainfall conditions (Table 2). The design-storm set combined three durations (24, 72, and 168 h) with four return periods (10, 20, 50, and 100 years), using design depths derived from the 1980–2024 rainfall record at Haining national meteorological station. Temporal rainfall patterns were generated with an index-storm method. Four historical events were also included and denoted T1–T4: two typhoon events, one common spring rainfall event, and one 14-day plum-rain sequence. Tidal boundary conditions were taken from observed records at Haining station, with an adverse 1996 tidal sequence applied to the design storms according to local flood-control practice. Each scenario was simulated under both regulation-based and storage–discharge balance scheduling, giving 32 simulations in total.

Table 2. Summary of rainfall scenarios.

Group	No.	Duration (h)	Return period/type	Rainfall range (mm)
Design storms	12	24, 72, 168	10-100 yr	159.1-451.9
Historical events	4	24-336	typhoon, spring, plum-rain	31.8-297.0

Scheduling strategy comparison

Drainage performance was evaluated using four indicators: reach exceedance ratio r_{ex} , maximum exceedance duration T_{ex} , maximum exceedance depth D_{ex} , and peak water level at Chang'an station Z_{CA} . Compared with regulation-based scheduling, storage–discharge balance scheduling substantially reduced the spatial extent of above-warning water levels, but had only limited influence on peak water levels during extreme design storms (Table 3).

The benefit of storage–discharge balance scheduling was clearest for short design storms and long plum-rain sequences. For 24 h design storms, the reduction in r_{ex} was about 20–25 percentage points; for 72 h design storms it was about 12–25 points. The 168 h scenarios showed a strong dependence on rainfall type. Sustained low-intensity plum-rain cases allowed repeated proactive drainage and achieved reductions of about 26 points in r_{ex} and 13.4–17.0 h in T_{ex} , whereas high-return-period typhoon cases left little operational margin.

Table 3. Main performance changes under storage-discharge balance scheduling relative to regulation-based scheduling.

Scenario group	Main benefit	Limited effect
24 h design storms	r_{ex} reduced by about 20-25 percentage points	Z_{CA} reduced by no more than 0.02 m
72 h design storms	r_{ex} reduced by about 12-25 percentage points	T_{ex} reduced by no more than 1.5 h
168 h design storms	Low-return-period 168 h cases reduced by about 26 points in r_{ex} and 13.4-17.0 h in T_{ex}	High-return-period 168 h cases improved only slightly
Historical T4	T_{ex} reduced from 86.0 to 49.2 h, a 42.8% relative reduction	Peak reduction remained modest

In contrast, peak-level indicators changed little in design storms. Across the design-storm matrix, reductions in D_{ex} were 0–0.03 m and reductions in Z_{CA} were 0–0.05 m. This indicates that scheduling can reduce exceedance extent and persistence by using storage earlier, but once the storm peak arrives, outlet structures operate near capacity and peak water levels are governed mainly by the physical drainage capacity. Among the historical scenarios, T1 closely matched the D24h-10 response, T3 produced no exceedance under either strategy, and T4 showed the largest relative reduction in exceedance duration because its 14-day rainfall sequence provided repeated drainage windows between rainfall peaks.

System optimization

System optimization was tested for four scenarios around the current local design standard of 10-year drainage: D24h-10, D24h-20, D72h-10, and D72h-20. Three measures were considered under storage–discharge balance scheduling: lowering management control levels, adding a pumping station on the western Xintang River, and combining the lowest tested control level (Chang'an 2.06 m) with added pumping capacities of 20 and 40 m³ s^{−1}.

Table 4. Summary of optimization effects.

Measure	Main effect	Implication
Lower control levels	Provides additional pre-event storage, but changes in exceedance duration and peak level are modest	Useful as an operational adjustment, but insufficient to remove 20-year drainage stress
Added pumping	Shortens T_{ex} and lowers Z_{CA} , with little change in r_{ex}	Addresses post-peak drawdown; marginal duration gains weaken beyond about 20 m ³ s ^{−1}
Joint scheme	Produces the strongest overall improvement by combining pre-event storage and added discharge capacity	Q20+CL2.06 is balanced; Q40+CL2.06 gives the largest reduction for D72h-20

The optimization results indicate that the main limitation is structural outlet capacity rather than only operating logic. Lowering control levels creates antecedent storage and slightly reduces exceedance duration, but the peak-level reduction remains only centimetre-scale. Added pumping has little effect on the first onset of above-warning levels, but it directly increases discharge capacity and therefore accelerates drawdown after the river network has filled. The marginal benefit in exceedance duration declines beyond about 20 m³ s^{−1}, especially for 72 h storms. The joint schemes perform best because the two measures act on different phases of drainage: lower control levels increase pre-storm storage, while additional pumping releases the stored volume more rapidly. This combined effect is most valuable for reducing prolonged high-water stress under storms around and above the current drainage standard.

DISCUSSION

Mechanisms behind scheduling-performance differences

The contrast between regulation-based and storage–discharge balance scheduling is essentially a contrast between threshold response and process response. Regulation-based scheduling is simple and consistent with routine operation, but it mobilizes drainage capacity only after water levels reach

prescribed thresholds. In a low-gradient river network, this reactive logic leaves little room to use available storage before warning levels are exceeded. Storage–discharge balance scheduling instead links the discharge target to the evolving inflow–outflow imbalance, moving the operation closer to feedback control (García et al., 2015; Lund et al., 2018; Horváth et al., 2022).

This mechanism explains why the main improvement appears in exceedance extent and duration. Early drawdown increases the buffer volume available before vulnerable reaches cross warning levels, especially for short design storms and long plum-rain sequences with repeated inter-peak drainage windows. It also explains why peak indicators respond much less. Near the storm peak, outlet structures tend to operate close to capacity under both strategies, so water levels are governed mainly by physical conveyance, external boundary conditions, and discharge capacity. Scheduling therefore improves the use of existing storage, but peak-level control under extreme storms still depends on physical capacity improvements.

Interpretation of optimization measures

The tested optimization measures act on different phases of drainage. Lowering the management control level acts before the storm by creating additional antecedent storage, so its effect is mainly to delay the onset of warning-level exceedance. Its influence on peak level is limited because it does not increase the rate at which water can leave the system. The added pumping station acts during and after the storm by increasing outlet capacity. It has little effect on the first onset of exceedance, but it shortens exceedance duration and lowers peak water levels once the network has filled.

The joint schemes are most effective because they combine these complementary functions: lower control levels prepare storage before the event, while added pumping capacity releases that storage more rapidly during and after the event. The diminishing duration gains beyond about $20 \text{ m}^3 \text{ s}^{-1}$ indicate that, after additional outlet capacity is provided, the active bottleneck shifts toward internal conveyance, distributed storage release, and receiving-water constraints. Thus, operational drawdown and engineering capacity expansion should be evaluated together rather than as independent measures. The Q20+CL2.06 scheme offers a balanced improvement near the current drainage standard, whereas Q40+CL2.06 provides greater protection for the more demanding D72h-20 scenario.

Model strengths and remaining limitations

The coupled model provides several practical advantages for drainage assessment in plain river network irrigation districts. It links rainfall runoff, internal storage, river-network hydrodynamics, and structure scheduling within a single simulation framework, so the hydraulic consequences of different operation rules can be compared under identical rainfall and boundary conditions. The use of conceptual ponds keeps the model tractable at district scale while retaining the storage and delayed drainage effect of the dense internal ditch–pond system. The model also represents bidirectional flows, backwater effects, and controllable gates and pumps, which are central to drainage behavior in lowland regulated networks.

Some limitations remain. The conceptual pond representation is appropriate for reproducing backbone-channel water levels, but it cannot identify which individual minor channels control local field-to-ditch exchange. In addition, the present analysis focuses on hydraulic indicators; farm-scale inundation, crop damage, energy cost, and pump reliability would be needed for final investment decisions. Operational deployment would also require rainfall and tidal forecasts, reliable telemetry, and uncertainty-aware updating. These requirements point to future development toward forecast-based scheduling or model predictive control, particularly for long-duration plum-rain events.

CONCLUSIONS

This study developed a coupled rainfall-runoff, conceptual storage, hydrodynamic, and scheduling model for drainage assessment in a plain river network irrigation district. The model reproduced observed water levels well, with district-wide NSE values of 0.997 and 0.988 for calibration and validation and $\text{NSE} \geq 0.881$ at all 11 stations. Scenario analysis showed that storage–discharge balance

scheduling mainly reduces the spatial extent and persistence of above-warning water levels: reach exceedance ratios were reduced by up to 25 percentage points in design storms, and exceedance duration in the 14-day plum-rain sequence decreased from 86.0 to 49.2 h. Peak water-level reductions were limited (≤ 0.05 m), indicating that extreme-peak control requires physical capacity improvement. Optimisation tests further showed that lowering control levels and adding pumping capacity are complementary, with joint schemes providing the most robust drainage improvement.

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