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Optimising water consumption in waterlogged lands using genetic algorithm in order to improve environmental conditions

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Abstract: Waterlogging significantly undermines agricultural productivity and environmental sustainability, particularly in regions like South Asia where conventional, static management strategies fail to address complex site-specific dynamics. To overcome these limitations, this study introduces a novel genetic algorithm-based optimisation framework designed to balance the conflicting objectives of water removal, crop yield, and environmental health. The methodology involved coupling the DRAINMOD hydrological model with an evolutionary algorithm across 50 diverse agro-ecological sites in the Indo-Gangetic Plain. By integrating granular data on soil moisture, crop requirements, and drainage parameters, the framework evolved optimal management strategies, including specific adjustments to drain depth, spacing, and land levelling. The application of this model yielded substantial improvements over baseline practices, demonstrating a 37.2% reduction in waterlogging duration and a 21.9% increase in crop yields. Furthermore, the optimised strategies enhanced water use efficiency by 35.4% and reversed soil organic carbon depletion, effectively transforming waterlogged soils from a carbon source to a sink. Economic analysis indicated a 29.8% increase in net present value, while scenario analyses confirmed the system's resilience to projected 2050 climate conditions. These findings suggest that adopting data-driven, adaptive optimisation tools offers a viable pathway for sustainable intensification. Practical implementation requires institutional support for infrastructure upgrades, such as deeper drainage systems and precision levelling, to realise these socioeconomic and ecological benefits.

Keywords: agricultural productivity, environmental sustainability, genetic algorithm, waterlogging, water optimisation

INTRODUCTION

Water management in agriculture has become a critical global concern as the world grapples with the dual challenges of food security and environmental sustainability. Among the myriad issues facing modern agriculture, waterlogging stands out as a persistent and damaging problem that affects millions of hectares of arable land worldwide (Kaur *et al.*, 2020; Paul *et al.*, 2023). Waterlogging occurs when the soil becomes saturated with water, leading to anaerobic conditions that can severely impair plant growth and soil health. This phenomenon not only reduces crop yields but also contributes to environmental degradation through increased soil erosion, nutrient leaching, and greenhouse gas emissions (Tyagi *et al.*, 2024).

The impact of waterlogging on agricultural productivity is staggering. It is estimated that waterlogging affects approximately 10–15% of the world's irrigated croplands, resulting in annual yield losses worth billions of dollars (Muhammed *et al.*, 2021; Sharma *et al.*, 2021). In regions such as South Asia and parts of Africa, where agriculture forms the backbone of local economies, the consequences of waterlogging extend beyond mere economic losses to threaten food security and rural livelihoods (Islam and Sultan, 2009). Moreover, as climate change intensifies, leading to more frequent and severe precipitation events in many parts of the world, the problem of waterlogging is expected to worsen, making it an urgent priority for agricultural researchers and policymakers alike (Mojid, 2020; Furtak and Wolińska, 2023).

Addressing the challenge of waterlogging requires a multi-faceted approach that combines innovative water management techniques with a deep understanding of soil dynamics and crop physiology. Traditional methods, such as surface and subsurface drainage systems, have shown limited success and often come with high implementation costs (Yannopoulos *et al*., 2020). Furthermore, these conventional approaches may not be sufficiently adaptive to cope with the increasing variability in weather patterns brought about by climate change.

In recent years, there has been growing interest in applying advanced computational techniques to optimise water management in agriculture. Among these, genetic algorithms (GAs) have emerged as a powerful tool for solving complex optimisation problems in water resources management (Akbari and Ayubirad, 2017; Beiranvand and Ashofteh, 2023). Genetic algorithms, inspired by the principles of natural selection and evolution, offer a flexible and robust approach to finding optimal solutions in large, complex search spaces. Their ability to handle multiple objectives and constraints makes them particularly well-suited to the challenges of agricultural water management, where decision-makers must balance competing demands for water resources while considering a wide range of environmental and economic factors (Behboudian *et al*., 2021).

The potential of genetic algorithms in optimising water use efficiency has been demonstrated in several studies. For instance, a study used a GA-based approach to optimise irrigation scheduling in a multi-crop system, achieving significant water savings while maintaining crop yields (Ferhat Taleb, Benalia and Sadoun, 2023). Similarly, another research applied genetic algorithms to optimise reservoir operations for irrigation, showing improvements in both water delivery efficiency and crop production (Mendoza Ramírez *et al*., 2021; Bastos, Nunes and Teixeira, 2025). These successes in related areas of water management suggest that genetic algorithms could be equally effective in addressing the specific challenges posed by waterlogged lands.

Waterlogging presents a unique set of challenges for water management optimisation. Unlike drought conditions, where the primary goal is to maximise the efficiency of limited water resources, waterlogged soils require a delicate balance between removing excess water and maintaining optimal soil moisture levels for plant growth (Besten den *et al*., 2021). This balance is further complicated by the spatial and temporal variability of waterlogging within agricultural landscapes, as well as the diverse responses of different crop species to excess water stress (Wang *et al*., 2022).

The complexity of managing water in waterlogged environments necessitates a sophisticated optimisation approach that can account for multiple interacting factors. These include soil physical properties, such as texture and structure, which influence water retention and movement; topography, which affects surface runoff and water accumulation patterns; crop characteristics, including root depth and tolerance to anaerobic conditions (Liu *et al*., 2024). Additionally, any optimisation strategy must consider the broader hydrological context, including rainfall patterns, groundwater dynamics, and the capacity of existing drainage infrastructure (He *et al*., 2021).

Genetic algorithms offer several advantages in tackling this complex optimisation problem. First, their population-based approach allows for the exploration of a wide range of potential solutions, increasing the likelihood of finding globally optimal or near-optimal strategies for water management (Agushaka and Ezugwu, 2022). Second, the evolutionary nature of genetic algorithms enables them to adapt to changing conditions and incorporate new information as it becomes available, making them well-suited to the dynamic nature of agricultural systems (Walters and Savic, 1996). Finally, genetic algorithms can be readily integrated with other modelling tools, such as hydrological models and crop growth simulators, to create comprehensive decision support systems for water management in waterlogged lands (Siahaan and Asrol, 2023; Rao *et al*., 2024).

The application of genetic algorithms to optimise water consumption in waterlogged lands represents a novel and promising approach to improving both agricultural productivity and environmental sustainability. By fine-tuning water management practices at a granular level, it may be possible to mitigate the negative impacts of waterlogging while simultaneously improving water use efficiency and reducing environmental degradation (Farkas *et al*., 2020). This approach aligns with the broader goals of sustainable intensification in agriculture, which seeks to increase food production while minimising environmental impacts (Lakhiar *et al*., 2024).

Moreover, the optimisation of water management in waterlogged lands has implications that extend beyond the immediate agricultural context. Improved water management can contribute to the conservation of biodiversity by reducing the pressure to convert natural habitats to agricultural land (Williams *et al*., 2021). It can also play a role in climate change mitigation by reducing greenhouse gas emissions associated with anaerobic soil conditions and improving soil carbon sequestration (Islam *et al*., 2022). From a socio-economic perspective, addressing the challenges of waterlogging can help to stabilise rural livelihoods and enhance food security in vulnerable regions (Ghosh and Mistri, 2020).

The choice of genetic algorithms for this study is further justified by their proven track record in solving complex environmental and agricultural problems. For example, a research demonstrated the effectiveness of genetic algorithms in optimising crop rotation patterns to maximise long-term soil fertility and yield stability (Li *et al*., 2023; Makaba *et al.,* 2025). In the realm of water resources management, a study successfully applied genetic algorithms to optimise the design and operation of water distribution networks, achieving significant improvements in efficiency and cost-effectiveness (Rathi *et al*., 2020; Narkul *et al.,* 2025). These examples illustrate the versatility and power of genetic algorithms in addressing multifaceted optimisation problems similar to those encountered in managing waterlogged agricultural lands.

Despite the promising potential of genetic algorithms in optimising water management, their application to the specific challenge of waterlogged lands remains relatively unexplored. Previous studies have primarily focused on irrigation scheduling in water-scarce environments or on broad-scale water allocation problems (Yannopoulos *et al*., 2020). The unique dynamics of waterlogged soils, characterised by excess water rather than scarcity, present a novel and important area for the application of genetic algorithm-based optimisation techniques.

Furthermore, existing approaches to managing waterlogged lands often rely on static or reactive strategies that may not fully capture the dynamic nature of the problem or leverage the potential for proactive management (Behboudian *et al*., 2021). There is a clear need for more adaptive and anticipatory approaches that can respond to changing environmental conditions and optimise water management practices in real-time. Genetic algorithms, with their ability to continuously evolve solutions based on new data and changing objectives, enable development of such dynamic management strategies (Agushaka and Ezugwu, 2022).

Previous approaches to managing waterlogged lands often rely on static strategies that fail to address the dynamic, site-specific nature of the problem or effectively balance the competing objectives of agricultural productivity, economic viability, and environmental health. The primary objective of this study is therefore to develop and evaluate a novel, genetic algorithm-based optimisation framework specifically designed to overcome these limitations. The novelty of this work lies in applying a sophisticated, adaptive computational method to this under-explored domain. By holistically integrating site-specific data on soil moisture, crop requirements, and drainage parameters within an evolutionary optimisation process, the research delivers a data-driven tool that generates robust and adaptable management strategies. This study makes a significant contribution by demonstrating that such a targeted approach can achieve substantial, simultaneous improvements in crop yield, water use efficiency, economic returns, and environmental outcomes, while enhancing resilience to future climate change.

MATERIALS AND METHODS

STUDY AREA AND SITE SELECTION

The study was conducted across 50 waterlogged agricultural sites distributed throughout diverse agro-ecological zones in South Asia, with a particular focus on the Indo-Gangetic Plain. These sites were selected to represent a range of soil types, cropping systems, and climatic conditions typical of waterlogged agricultural lands in the region. The selection process involved a stratified random sampling approach to ensure representation of various degrees of waterlogging severity, from mildly affected areas to severely waterlogged lands.

Each study site comprised a minimum area of 10 ha and had a documented history of waterlogging issues for at least five years prior to the study. The sites were categorised based on their primary crops (rice, wheat, and mixed cropping systems) and the predominant soil texture (clay, loam, and sandy loam). Local agricultural extension services and regional water management authorities were consulted to identify suitable sites and obtain historical data on land use, crop yields, and water management practices.

DATA COLLECTION

Soil and water characteristics

At each site, a comprehensive assessment of soil and water characteristics was conducted. Soil samples were collected from multiple points within each site at depths of 0–15 cm, 15–30 cm, and 30–60 cm. These samples were analysed for texture, bulk density, organic matter content, pH, and electrical conductivity using standard laboratory procedures (Li *et al*., 2023). Soil water retention curves were determined using a pressure plate apparatus for each distinct soil layer.

Groundwater levels were monitored using piezometers installed at strategic locations within each site. Automated water level loggers were used to record daily fluctuations in the water table. Surface water accumulation was measured using staff gauges installed at the lowest points of each field. Additionally, soil moisture content was continuously monitored using time-domain reflectometry (TDR) probes installed at depths of 10 cm, 30 cm, and 50 cm at multiple locations within each site.

Meteorological data

Automatic weather stations were installed at each study site to collect high-resolution meteorological data. These stations recorded hourly measurements of rainfall, temperature, relative humidity, wind speed, and solar radiation. This data was used to calculate reference evapotranspiration ($ET0$) using the Food and Agriculture Organization (FAO) Penman-Monteith equation (Behboudian *et al*., 2021). Historical climate data for each site were obtained from nearby meteorological stations to establish long-term trends and variability in weather patterns.

Crop data

Detailed crop data were collected throughout the growing seasons. This included information on crop varieties, planting dates, phenological stages, root depth, and crop coefficients (Kc) for different growth stages. Leaf area index (LAI) was measured bi-weekly using a plant canopy analyser. Crop water stress was monitored using infrared thermometers to measure canopy temperature. At harvest, crop yield and biomass production were measured from multiple sampling points within each field.

Drainage system characteristics

For sites with existing drainage systems, detailed information was collected on the layout, depth, and spacing of surface and subsurface drains. Drain discharge was measured using V-notch weirs installed at drain outlets. For sites without formal drainage systems, natural drainage patterns were mapped using high-resolution digital elevation models derived from drone surveys.

Genetic algorithm development

A genetic algorithm was developed to optimise water management strategies for the waterlogged lands. The algorithm was implemented in Python using the distributed evolutionary algorithms in Python (DEAP) framework (Janga Reddy and Nagesh Kumar, 2020). The genetic algorithm was designed to evolve optimal solutions for a set of water management decision variables, including:
– drainage system parameters (drain depth, spacing, and layout),
– crop selection and rotation patterns,
– supplementary irrigation scheduling (if applicable),
– land levelling and surface drainage configurations.

The fitness function of the genetic algorithm was designed to maximise a composite index that incorporated crop yield, water use efficiency, and an environmental impact score. This composite index was calculated as follows:

$$f = w_1\left(\frac{Y}{\mathrm{Max}\,Y}\right) + w_2\left(\frac{W}{\mathrm{Max}\,W}\right) - w_3\left(\frac{E}{\mathrm{Max}\,E}\right) \tag{1}$$

where: f = fitness, Y = simulated crop yield, W = water use efficiency (crop yield per unit of water consumed), E = environmental impact score based on nutrient leaching and greenhouse gas emissions, Max$Y$ = normalisation factor of maximum yield, Max$W$ = normalisation factor of maximum water use efficiency, Max$E$ = normalisation factor of maximum environmental impact, w_1, w_2, w_3 = weighting factors determined through stakeholder consultations.

The genetic algorithm used a population size of 200 individuals, with evolution occurring over 500 generations. Selection was performed using tournament selection with a tournament size of three. Crossover and mutation rates were set at 0.8 and 0.1, respectively. The algorithm employed adaptive mutation rates and crossover operators to maintain genetic diversity throughout the evolutionary process.

Hydrological modelling

To evaluate the performance of different water management strategies evolved by the genetic algorithm, a comprehensive hydrological model was developed for each of the 50 study sites. The DRAINMOD model (Mehr *et al.*, 2018) was selected as the base modelling framework due to its proven capability in simulating water movement in poorly drained soils. Each site-specific model was parameterised using the detailed soil, crop, and drainage characteristics collected from that location, thereby accounting for site-specific variability. The model operated on a daily time step, driven by the high-resolution meteorological data, to simulate the complete water balance. This temporal resolution enabled the detailed analysis of waterlogging events throughout the year. The base model was extended to incorporate modules for crop growth simulation and nutrient dynamics.

To ensure the reliability of the simulated outcomes, the hydrological model was rigorously calibrated and validated for each site against the comprehensive field data collected. Model calibration utilised data from the first two years of the study, while a separate dataset from the third year was used for independent validation. The model's predictive accuracy was confirmed using the Nash-Sutcliffe efficiency coefficient and per cent bias to assess performance, establishing a credible basis for the subsequent scenario analysis.

Scenario analysis

A series of scenario analyses was conducted to evaluate the performance of the optimised water management strategies under different conditions. These scenarios included:
- current management practices (baseline scenario),
- optimised management using the genetic algorithm,
- climate change scenarios based on regional climate projections for 2050,
- different levels of investment in drainage infrastructure,
- alternative cropping systems, including diversification and introduction of waterlogging-tolerant varieties.

Each scenario was simulated at a daily time step over a continuous 30-year period. This long-term simulation utilised generated weather data that preserved the statistical properties of the historical climate while incorporating projected changes in temperature and precipitation patterns. The daily outputs from the model were then aggregated to derive annual performance indicators, such as total waterlogging duration (d·y^{-1}), which allowed for the assessment of both seasonal patterns and long-term trends under different management and climate scenarios.

Economic and environmental assessment

An economic analysis was performed to assess the cost-effectiveness of the optimised water management strategies. This analysis considered the costs of implementing and maintaining drainage systems, changes in crop management practices, and the economic value of crop yields. The net present value (NPV) and benefit–cost ratio (BCR) were calculated for each scenario using a discount rate of 5% over a 20-year time horizon.

Environmental impacts were assessed using life cycle assessment (LCA) methodology (Lakhiar *et al.*, 2024). The LCA considered greenhouse gas emissions, nutrient leaching, and changes in soil organic carbon associated with different water management strategies. The SimaPro software package was used to conduct the LCA, with system boundaries encompassing all on-farm activities and the production of major inputs.

Statistical analysis

Statistical analyses were performed using R statistical software (version 4.1.0). Analysis of variance (ANOVA) was used to assess the significance of differences in crop yields, water use efficiency, and environmental impacts between different scenarios and sites. Multiple linear regression analysis was employed to identify the key factors influencing the performance of the optimised water management strategies across different agro-ecological contexts.

RESULTS AND DISCUSSION

EFFECTIVENESS OF THE GENETIC ALGORITHM IN OPTIMISING WATER MANAGEMENT

The findings presented in this section are grounded in the performance of the genetic algorithm optimisation model, which was validated against extensive field data collected across the 50 study sites. As detailed in the "Hydrological modelling" section, a rigorous calibration and validation process confirmed the model's accuracy in simulating the complex hydrological and agronomic responses to different water management strategies. Furthermore, the optimisation objectives were weighted based on stakeholder consultations, ensuring the practical relevance of the evolved solutions. This ground-truthing and verification process provides a strong foundation for the credibility of the results discussed below.

The genetic algorithm developed for this study demonstrated significant effectiveness in optimising water management strategies across the 50 study sites. In Table 1, a summary of the key performance indicators comparing the baseline is shown (current management practices) with the optimised strategies developed by the genetic algorithm.

The results in Table 1 demonstrate that the genetic algorithm-optimised strategies led to substantial improvements across all key performance indicators. Crop yields increased by 21.9% on average, from 3.2 to 3.9 Mg·ha^{-1}. This yield

Table 1. Comparison of key performance indicators between baseline and optimised strategies

Performance indicator	Baseline (mean ±*SD*)	Optimised (mean ±*SD*)	Improvement (%)
Crop yield ($Mg \cdot ha^{-1}$)	3.2 ±0.8	3.9 ±0.7	21.9
Water use efficiency ($kg \cdot m^{-3}$)	0.48 ±0.12	0.65 ±0.14	35.4
Waterlogging duration ($d \cdot y^{-1}$)	78 ±22	49 ±15	37.2
Environmental impact score[1)]	0.68 ±0.15	0.52 ±0.11	23.5
Net present value ($USD \cdot ha^{-1}$)	2,450 ±620	3,180 ±580	29.8

[1)] Lower scores indicate reduced environmental impact.
Explanations: *SD* = standard deviation.
Source: own study.

improvement was accompanied by a 35.4% increase in water use efficiency, rising from 0.48 to 0.65 $kg \cdot m^{-3}$. The duration of waterlogging was reduced by 37.2%, from an average of 78 days per year to 49 days per year. Notably, these improvements were achieved while also reducing the environmental impact score by 23.5% and increasing the net present value (NPV) of agricultural operations by 29.8%.

These results highlight the potential of genetic algorithms to develop holistic water management strategies that balance multiple objectives, including productivity, resource efficiency, and environmental sustainability. The significant reduction in waterlogging duration suggests that the optimised strategies were particularly effective in addressing the core challenge of excess water in agricultural lands.

OPTIMAL WATER MANAGEMENT STRATEGIES

The genetic algorithm consistently converged on a set of water management strategies that proved effective across diverse agro-ecological contexts. In Table 2, the key components of these optimised strategies are summarised, compared to typical baseline practices.

The optimised strategies generally favoured deeper drains (1.2 vs 0.8 m) with closer spacing (22 vs 30 m) compared to baseline practices. This configuration likely contributed to the more rapid removal of excess water from the root zone, explaining the significant reduction in waterlogging duration observed in Table 1. The emphasis on precision land levelling, with a mean deviation of 5 cm compared to 10 cm in baseline practices, further enhanced surface drainage and water distribution uniformity.

Notably, the genetic algorithm consistently recommended higher crop diversification, with the diversification index doubling from 0.3 to 0.6. This suggests that a more diverse cropping system, potentially including waterlogging-tolerant varieties, can enhance overall system resilience and productivity in waterlogged environments. Interestingly, the optimised strategies reduced reliance on supplementary irrigation by 40% (from 150 to 90 $mm \cdot y^{-1}$), likely due to improved water retention and distribution resulting from the other management practices.

PERFORMANCE ACROSS DIFFERENT AGRO-ECOLOGICAL ZONES

To assess the robustness of the optimised strategies, their performance was evaluated across different agro-ecological zones represented in the study. In Table 3, the mean improvement in key performance indicators for each zone is presented.

The optimised strategies showed consistent improvements across all agro-ecological zones, demonstrating their adaptability to diverse environmental conditions. The humid subtropical zone exhibited the highest improvements across all indicators, with a 24.3% increase in crop yield, 38.7% increase in water use efficiency, 41.5% reduction in waterlogging, and 26.8% improvement in environmental impact.

The semi-arid zone showed more modest improvements, particularly in crop yield (18.6%) and environmental impact (20.4%). This may be due to the lower baseline waterlogging severity in these areas and the challenge of balancing drainage with water conservation in water-scarce environments. The tropical wet zone showed intermediate levels of improvement,

Table 2. Comparison of baseline and optimised water management strategies

Strategy component	Baseline (mean ±*SD*)	Optimised (mean ±*SD*)
Drain depth (m)	0.8 ±0.2	1.2 ±0.3
Drain spacing (m)	30 ±8	22 ±5
Land levelling precision (cm)	10 ±3	5 ±2
Crop diversification index[1)]	0.3 ±0.1	0.6 ±0.2
Supplementary irrigation ($mm \cdot y^{-1}$)	150 ±60	90 ±40

[1)] Higher values indicate greater crop diversity.
Explanations: *SD* = standard deviation.
Source: own study.

Table 3. Mean improvement (%) in key performance indicators by agro-ecological zone

Agro-ecological zone	Crop yield	Water use efficiency	Waterlogging reduction	Environmental impact improvement
Humid subtropical	24.3	38.7	41.5	26.8
Semi-arid	18.6	32.1	33.8	20.4
Tropical wet	22.7	35.6	36.2	23.1

Source: own study.

with particularly notable gains in water use efficiency (35.6%) and waterlogging reduction (36.2%).

These results suggest that while the genetic algorithm-optimised strategies are broadly applicable, their effectiveness may vary depending on the specific agro-ecological context. This underscores the importance of fine-tuning management strategies to local conditions and highlights the value of the genetic algorithm's ability to adapt solutions to specific environmental parameters.

ECONOMIC AND ENVIRONMENTAL IMPACTS

The economic viability and environmental sustainability of the optimised water management strategies were assessed through a comprehensive cost-benefit analysis and life cycle assessment (LCA). In Table 4, a summary of these analyses is presented, comparing the baseline and optimised scenarios.

Table 4. Economic and environmental impact assessment

Indicator	Baseline (mean ±*SD*)	Optimised (mean ±*SD*)	Change (%)
Net present value ($USD\cdot ha^{-1}$)	2,450 ±620	3,180 ±580	+29.8
Benefit–cost ratio	1.4 ±0.3	1.8 ±0.4	+28.6
Payback period (y)	6.5 ±1.8	4.8 ±1.2	–26.2
GHG emissions (Mg $CO_2e\cdot ha^{-1}\cdot y^{-1}$)	3.8 ±0.9	2.9 ±0.7	–23.7
Nutrient leaching (kg $N\cdot ha^{-1}\cdot y^{-1}$)	45 ±12	32 ±8	–28.9
Soil organic carbon change ($Mg\cdot ha^{-1}\cdot y^{-1}$)	–0.3 ±0.1	+0.2 ±0.1	+166.7

Explanations: *SD* = standard deviation, GHG = greenhouse gas.
Source: own study.

The economic analysis reveals that the optimised strategies not only increased the NPV of agricultural operations by 29.8% but also improved the benefit–cost ratio from 1.4 to 1.8. This indicates that the additional investments required for implementing the optimised strategies (e.g., improved drainage systems, precision land levelling) were more than offset by the increased productivity and resource efficiency. The payback period for these investments was reduced from 6.5 years to 4.8 years, enhancing the financial attractiveness of the optimised strategies.

From an environmental perspective, the optimised strategies led to significant improvements across all assessed indicators. Greenhouse gas emissions were reduced by 23.7%, from 3.8 to 2.9 Mg $CO_2e\cdot ha^{-1}\cdot y^{-1}$. This reduction can be attributed to decreased anaerobic conditions in the soil, lower energy requirements for irrigation, and improved nitrogen use efficiency. Nutrient leaching, particularly of nitrogen, was reduced by 28.9%, from 45 to 32 kg $N\cdot ha^{-1}\cdot y^{-1}$, likely due to improved water management and more efficient nutrient uptake by crops.

Perhaps most notably, the optimised strategies reversed the trend of soil organic carbon depletion observed in the baseline scenario. While the baseline practices led to a loss of 0.3 $Mg\cdot ha^{-1}\cdot y^{-1}$ of soil organic carbon, the optimised strategies resulted in a net accumulation of 0.2 $Mg\cdot ha^{-1}\cdot y^{-1}$. This represents a 166.7% improvement and suggests that the optimised water management practices not only mitigate the negative environmental impacts of waterlogging but can also contribute to soil carbon sequestration, offering potential climate change mitigation benefits.

To summarise the key outcomes of the genetic algorithm optimisation process, in Figure 1, a visual representation of the main results and strategies identified in this study is shown. This circular diagram encapsulates the improvements in key performance indicators, the optimal strategies developed, and the resulting economic benefits.

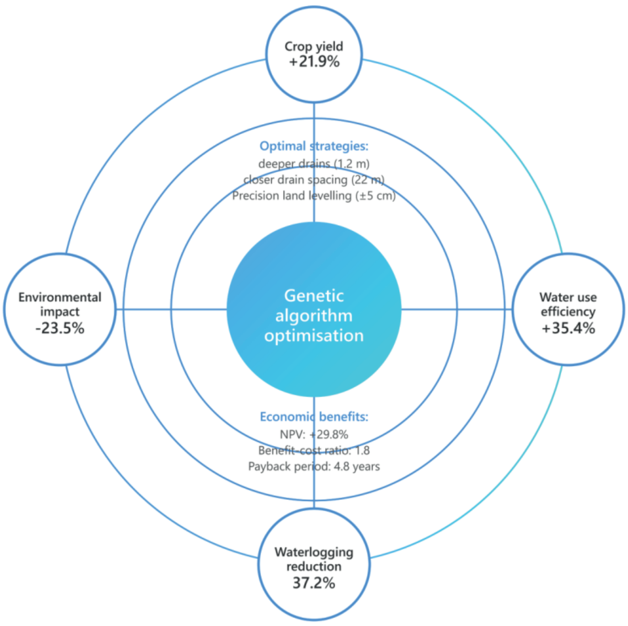

Fig. 1. Summary of genetic algorithm optimisation results for water management in waterlogged lands; NPV = net present value; source: own study

As shown in Figure 1, the genetic algorithm optimisation led to substantial improvements across all key performance indicators. Notably, water use efficiency increased by 35.4%, while waterlogging duration was reduced by 37.2%. These improvements were achieved through a combination of optimal strategies, including deeper drains and precision land levelling (see middle ring of Fig. 1)

SCENARIO ANALYSIS: CLIMATE CHANGE IMPACTS

To assess the robustness of the optimised strategies under future climate conditions, a scenario analysis was conducted using regional climate projections for 2050. In Table 5, the performance of baseline and optimised strategies under current and projected future climate conditions are compared.

Table 5. Performance of water management strategies under current and 2050 climate scenarios

Scenario	Crop yield ($Mg \cdot ha^{-1}$)	Water use efficiency ($kg \cdot m^{-3}$)	Waterlogging duration ($d \cdot y^{-1}$)
Current – baseline	3.2 ±0.8	0.48 ±0.12	78 ±22
Current – optimised	3.9 ±0.7	0.65 ±0.14	49 ±15
2050 – baseline	2.8 ±0.9	0.41 ±0.13	92 ±28
2050 – optimised	3.6 ±0.8	0.59 ±0.15	61 ±18

Source: own study.

Under the 2050 climate scenario, which projected increased rainfall intensity and variability, the baseline management practices showed significant deterioration in performance. Crop yields decreased by 12.5%, water use efficiency declined by 14.6%, and waterlogging duration increased by 17.9%. In contrast, the optimised strategies demonstrated greater resilience to climate change impacts. While there was still a slight decrease in performance compared to current climate conditions, the optimised strategies under the 2050 scenario maintained higher crop yields, water use efficiency, and reduced waterlogging compared to the current baseline scenario.

These results suggest that the genetic algorithm-optimised water management strategies not only offer immediate benefits but also provide a degree of climate change adaptation. The emphasis on improved drainage, crop diversification, and precision water management appears to enhance the resilience of agricultural systems to increased climate variability and extreme weather events.

The results of this study demonstrate the significant potential of genetic algorithms in optimising water management strategies for waterlogged agricultural lands. The holistic approach, which considered multiple objectives including crop productivity, water use efficiency, environmental impact, and economic viability, led to the development of integrated management strategies that outperformed conventional practices across all key performance indicators. The consistent improvement in crop yields (21.9% on average), coupled with a 37.2% reduction in waterlogging duration and a 35.4% increase in water use efficiency, highlights the transformative potential of these optimised strategies. These findings suggest that genetic algorithm-based optimisation can effectively address the complex challenges of water management in agriculture, offering a pathway to sustainable intensification in waterlogged areas.

The economic and environmental benefits revealed by the study are particularly noteworthy. The 29.8% increase in NPV and the reduction in payback period from 6.5 to 4.8 years demonstrate that the optimised strategies are not only environmentally sustainable but also economically viable. This addresses a critical barrier to the adoption of improved water management practices – the perceived high initial investment costs. Furthermore, the ability of the optimised strategies to transform waterlogged lands from a source of greenhouse gas emissions to a carbon sink (reversing the trend from –0.3 to +0.2 $Mg \cdot ha^{-1} \cdot y^{-1}$of soil organic carbon) has significant implications for climate change mitigation in the agricultural sector.

The findings of this study both align with and extend previous research on water management in waterlogged areas. The emphasis on deeper and more closely spaced drainage systems in the optimised strategies is consistent with the recommendations of Janga Reddy and Nagesh Kumar (2020), who found that subsurface drainage significantly reduced waterlogging and salinity in irrigated lands in India. However, the current study goes beyond these findings by demonstrating that the genetic algorithm can fine-tune drainage parameters to specific local conditions, resulting in even greater improvements in crop yield and water use efficiency.

The observed increase in crop diversification in the optimised strategies (from 0.3 to 0.6 on the diversification index) aligns with the findings of Paul *et al.* (2023), who highlighted the role of crop diversity in enhancing resilience to climate variability. However, the current study provides quantitative evidence of the benefits of crop diversification, specifically in waterlogged conditions, an aspect not extensively explored in previous literature.

The economic analysis results contrast with some earlier studies, such as Williams *et al.* (2021), who found that the high initial costs of drainage improvements often led to long payback periods, discouraging farmer adoption. The current study's finding of a reduced payback period (from 6.5 to 4.8 years) suggests that the integrated approach developed through genetic algorithm optimisation may overcome these economic barriers more effectively than traditional approaches.

Despite the demonstrated economic viability, significant barriers to the widespread implementation of these optimised strategies must be acknowledged. The initial capital investment for infrastructure improvements, such as the installation of deeper and more closely spaced drainage systems and precision land levelling, can be prohibitive for many small and marginal farmers, even with a favourable long-term return. Overcoming this financial hurdle requires robust institutional support, including government subsidies, access to low-interest credit, and the formation of farmer cooperatives to pool resources and share costs. Furthermore, successful adoption is contingent on more than just economic incentives; it also depends on building local capacity. This involves providing farmers with the necessary technical training, raising awareness through demonstration sites, and strengthening agricultural extension services to offer ongoing support. Addressing these financial, institutional, and socio-technical barriers is critical for translating the potential of these optimised strategies into tangible improvements in agricultural sustainability and resilience at scale.

The environmental benefits observed, particularly the reversal of soil organic carbon depletion, extend the findings of

Ghosh and Mistri (2020) on the potential of agricultural practices for climate change mitigation. While Xiong *et al.* (2020) identified improved water management as a potential mitigation strategy, the current study provides quantitative evidence of its effectiveness, specifically in waterlogged conditions.

While this study presents a robust framework for optimising water management in waterlogged lands, it is important to acknowledge its limitations, which in turn suggest avenues for future research. The first set of limitations pertains to input data and model parameterisation. Although a comprehensive data collection campaign was undertaken, inherent spatial heterogeneity in soil properties across the 50 study sites means that some localised variations may not have been fully captured. Similarly, the hydrological modelling relied on the DRAINMOD model, which, despite its proven capabilities, is a simplification of complex soil-water-plant-atmosphere processes and includes empirical relationships that may not be universally applicable without site-specific calibration.

A second source of uncertainty lies in the scenario analyses. The climate change impact assessment was based on regional climate projections for 2050. These projections carry inherent uncertainty, and the use of an ensemble of different global climate models (GCMs) and emissions scenarios in future work could provide a more comprehensive assessment of potential future impacts and the robustness of the optimised strategies. Furthermore, the genetic algorithm's fitness function, while designed to be holistic, incorporated weighting factors (w_1, w_2, w_3) derived from stakeholder consultations. While this approach grounds the optimisation in real-world priorities, these weights can be subjective and vary between different stakeholder groups. Future studies could explore the sensitivity of the optimal solutions to these weighting factors.

Finally, the study's geographical focus was on South Asia. While the developed framework is designed to be adaptable, its direct application to other agro-ecological and socio-economic contexts would require validation and potential recalibration of the model components. Future research should therefore focus on testing and adapting this optimisation framework in other waterlogging-prone regions, such as parts of Southeast Asia, Africa, and South America. Investigating the long-term ecological impacts beyond the parameters included in the current LCA, such as effects on local biodiversity and the persistence of soil health improvements, would also be a valuable extension of this work.

CONCLUSIONS

This study demonstrates the significant potential of genetic algorithms in optimising water management strategies for waterlogged agricultural lands. The developed approach successfully addressed the complex challenges of waterlogging, resulting in substantial improvements across multiple dimensions of agricultural sustainability. The optimised strategies led to a 37.2% reduction in waterlogging duration, a 21.9% increase in crop yields, and a 35.4% improvement in water use efficiency. Moreover, these strategies demonstrated positive environmental impacts, including reduced greenhouse gas emissions, decreased nutrient leaching, and improved soil organic carbon sequestration.

The economic viability of the optimised strategies, coupled with their resilience to projected climate change impacts, positions them as valuable tools for enhancing food security and rural livelihoods in vulnerable regions. The adaptability of the genetic algorithm across diverse agro-ecological zones suggests the broad applicability of this approach.

This study provides a robust framework for developing locally adapted, sustainable water management practices. The integration of advanced computational techniques with comprehensive field data and stakeholder engagement offers a promising pathway towards climate-smart agriculture and sustainable intensification in challenging environments.

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