Water-energy-food nexus-based irrigation planning for drought-prone agricultural regions: a case study of Gansu Province

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Abstract. Drought-prone irrigation districts increasingly face concurrent challenges of water scarcity, rising energy costs for water delivery and the obligation to maintain stable food production. This article develops an integrated water–energy–food nexus framework for irrigation planning in arid agricultural regions and applies it to a representative set of irrigation schemes in Gansu Province, north-western China. The framework links hydrological allocation, crop choice, irrigation scheduling and energy use for pumping within a unified multi-objective optimisation model. It evaluates trade-offs between reduced consumptive water use, lower energy demand, environmental flow protection and robust crop yields under recurrent drought. Scenario analysis shows that nexus-based irrigation plans can lower total irrigation withdrawals by around one fifth while reducing pumping energy requirements and sustaining staple grain output. The results demonstrate how coordinated management of water, energy and food objectives can enhance drought resilience in data-scarce, infrastructure-dependent farming landscapes. The approach is transferable to other semi-arid regions.

1 Introduction

Irrigated agriculture underpins food security in many dryland regions, yet it is increasingly exposed to hydrological droughts, competition for limited freshwater resources and rising energy prices. Traditional irrigation planning approaches have primarily focused on maximising crop yields subject to water availability constraints, often neglecting the energy implications of pumping and conveyance as well as broader environmental and social objectives. In parallel, policy debates on the water–energy–food nexus have highlighted the deep interdependencies between sectors, but operational tools for translating nexus concepts into farm and basin level irrigation decisions remain underdeveloped, particularly in data-scarce regions.

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Gansu Province in north-western China represents a critical test case for nexus-based irrigation planning. The province combines highly productive irrigated oases along major rivers with expansive arid and semi-arid landscapes that are acutely sensitive to climatic variability. Groundwater overdraft, declining environmental flows and recurrent agricultural droughts have emerged as major concerns, while energy-intensive pumping from deep aquifers and long-distance conveyance systems has tightened the link between irrigation decisions and regional energy systems. At the same time, Gansu is expected to sustain or even increase grain output to support national food security targets.

Against this background, there is a growing need for integrated planning approaches that jointly consider water allocation, energy use and food production outcomes across multiple spatial and temporal scales. Existing hydrological or economic models typically optimise a single objective, such as profit or yield, and treat the other dimensions as exogenous parameters. Such models are ill-suited to exploring trade-offs between consumptive water use, energy demand, environmental flow protection and yield stability under drought conditions. Moreover, many studies rely on stylised basin representations that do not reflect the operational constraints and institutional arrangements of real irrigation districts.

José A. Gómez-Limón and Rocío Granado-Díaz analyse demand for hydrological drought insurance in irrigated agriculture, showing how risk preferences and contract design influence uptake [1]. Yu Zhang, Zhen Wu and co-authors represent irrigation, crop growth and water demand jointly to describe agricultural drought in irrigated plains and to quantify management effects on drought severity [2]. Ji Eun Kim, Jung Ho Lee and Tae Woong Kim combine drought hazard indicators with response capacity to map regional drought risk in water supply systems [6]. Ming Li, Shihuai Zhou and colleagues propose a climate-smart irrigation strategy that reduces consumptive water use while maintaining food production under climate change, stressing the value of flexible allocation rules [3]. Pradip Deb, Hamid Moradkhani and co-authors link hydrology, crop growth and irrigation in an integrated modelling framework to estimate how supplemental irrigation mitigates drought-related yield losses [4]. Fawen Li, Manjing Zha and colleagues investigate how irrigation and groundwater jointly control the propagation of meteorological drought into agricultural drought through changes in aquifer storage [11].

Mahsa Sedighkia, Bithin Datta and Shahab Razavi formulate a multi-objective optimisation model for cropping pattern adjustment under irrigation water restrictions and environmental flow requirements, identifying trade-offs between income and ecological protection [5]. Saeed Sharghi and Reza Kerachian design a seasonal smart market for groundwater that coordinates pumping decisions among farmers and supports sustainable aquifer use [9]. Mehmet Erkan Soylu and Rafael L. Bras quantify irrigation benefits in agroecosystems limited by water and energy, linking water use to energy demand [7]. Ankur Agrawal, Bhavik R. Bakshi and co-authors develop a multi-objective optimisation framework for the food–energy–water nexus based on crop land allocation [10]. Muhammad Hafeez, Stefan Uhlenbrook and Philipp Schmitter emphasise that climate resilience depends on irrigation water management from farm to basin scale [8], while Bo Zhang, Peiling Wu and Xuejun Zhao integrate water deficit quantification, rainwater regulation and precision irrigation into a strategy for drought resistance [12].

2 Material and methods

The empirical work focuses on a set of major irrigation districts in Gansu Province that span the middle reaches of the Yellow River, interior basins and mountain piedmont oases. These systems are characterised by high dependence on surface water diversions and groundwater pumping, strong seasonal variability in river flows and a high frequency of agricultural droughts. The analysis combines hydrological, agronomic, energy and economic information for the period 2005–2023, drawing on basin authority records of water deliveries, provincial statistical yearbooks on crop areas and yields, power utility data on electricity use for pumping and field measurements of irrigation practices in representative farms.

All data are harmonised at the scale of irrigation district–crop combinations and expressed in consistent physical units of water volumes, energy consumption and crop output. A water–energy–food nexus indicator set is constructed, including total consumptive water use, pumping energy requirements, staple grain production, irrigation reliability and minimum environmental flow deficits. These indicators serve as inputs and outputs to a multi-objective optimisation model that generates alternative irrigation plans.

The optimisation problem minimises consumptive water use and pumping energy while maximising food production and irrigation reliability, subject to constraints on land availability, crop rotation requirements, canal and well capacities and environmental flow targets. Model structure is linear with yearly time steps and seasonal sub-periods, but drought representation is based on sequences of observed dry, normal and wet years, allowing before and after comparisons between historical allocation rules and nexus-based plans. Cluster analysis is then applied to classify irrigation districts into typologies according to water scarcity, energy intensity and production structure, providing a basis for transferring scenario results to similar regions within and beyond Gansu Province.

3 Results and discussion

The application of the water–energy–food nexus-based optimisation framework to the irrigation districts of Gansu Province reveals substantial potential to improve the balance between water savings, energy use and food production under drought conditions. Historical allocation rules put strong emphasis on stabilising cropped area and grain output, with irrigation withdrawals adjusted only when river flows were severely curtailed. This resulted in high consumptive water use, increasing dependence on groundwater and substantial pumping energy requirements, especially in districts located far from diversion points. Model simulations confirm that under recent drought sequences, historical practices expose irrigation districts to frequent shortfalls in environmental flow targets and to pronounced variability in irrigation reliability.

When nexus-based objectives are introduced, the model selects more heterogeneous cropping patterns, shifts irrigated area towards crops with higher water productivity and reduces over-irrigation in tail-end reaches. At the same time, it redesigns the spatial pattern of groundwater pumping to reduce energy-intensive lifts and to concentrate pumping in locations where hydraulic heads are lower and electricity tariffs are more favourable. These adjustments often leave aggregate grain production almost unchanged, even when total irrigation withdrawals decline markedly. However, the scale of achievable savings and the associated energy responses vary considerably across districts, reflecting differences in infrastructure, crop portfolios and access to groundwater. Understanding these differences is crucial for targeting policy interventions and investments. To explore these patterns more explicitly, four stylised planning strategies were compared across the ensemble of irrigation districts. The first strategy reproduces historical allocation rules, maintaining existing cropping patterns and irrigation schedules. The second strategy pursues a water-saving objective that minimises consumptive use subject to fixed production targets, without regard to energy costs. The third strategy minimises pumping energy, allowing water use and crop composition to adjust as long as minimum food production is maintained. The fourth strategy implements the full water–energy–food nexus optimisation, jointly balancing water savings, pumping energy and grain output while enforcing environmental flow requirements. For each strategy, the model produces aggregated indicators of annual irrigation withdrawals, pumping energy consumption, staple grain production and irrigation reliability averaged over representative drought sequences. These indicators are summarised in Table 1, which provides a compact overview of the performance of alternative strategies at provincial scale..

Table 1. Performance of alternative irrigation planning strategies in Gansu Province under representative drought sequences.

Planning strategy	Irrigation withdrawals (million cubic metres per year)	Pumping energy (gigawatt-hours per year)	Staple grain production (million tonnes per year)	Irrigation reliability index (0–1)
Historical allocation	4 800	1 050	7.2	0.74
Water-saving only	3 900	980	7.0	0.78
Energy-minimisation only	4 300	860	6.8	0.76
Water–energy–food nexus optimisation	3 950	820	7.1	0.83

The figures in Table 1 show that historical allocation rules are associated with the highest irrigation withdrawals and the largest pumping energy demand among the four strategies. Annual withdrawals of 4 800 million cubic metres and pumping energy of 1 050 gigawatt-hours deliver staple grain production of 7.2 million tonnes but provide only moderate irrigation reliability with an index value of 0.74. Pursuing a purely water-saving objective reduces withdrawals by about 900 million cubic metres, a decline of almost one fifth, while lowering pumping energy demand to 980 gigawatt-hours. Grain production falls slightly to 7.0 million tonnes, and reliability improves to 0.78 because water is reallocated towards districts and crops with higher marginal productivity.

The energy-minimisation strategy delivers a different trade-off. Irrigation withdrawals decline modestly to 4 300 million cubic metres, yet pumping energy falls more strongly to 860 gigawatt-hours because the model shifts pumping to locations with lower lifts and relies more on gravity-fed supplies. This comes at the cost of a more pronounced reduction in grain production to 6.8 million tonnes, even though reliability reaches 0.76. In practice, such a strategy might appeal in contexts where power system constraints or energy price shocks dominate policy concerns, but it may be politically difficult to accept sustained output losses in food-deficit regions.

The full water-energy-food nexus optimisation strategy achieves a more balanced outcome. Irrigation withdrawals are reduced to 3 950 million cubic metres, close to the level of the purely water-saving strategy, while pumping energy demand is cut to 820 gigawatt-hours, the lowest among all scenarios. Staple grain production is maintained at 7.1 million tonnes, only slightly below the historical reference, and irrigation reliability increases to 0.83. These simultaneous gains are achieved by combining moderate reductions in irrigated area for low-value, water-intensive crops with targeted investments in more efficient irrigation technologies, strategic relocation of pumping and modest adjustments in cropping calendars.

The comparison of strategies suggests that a narrowly defined focus on either water savings or energy cost reduction fails to exploit important synergies between water allocation, energy use and food production. The nexus-based approach, by contrast, identifies portfolios that respect environmental flow constraints, relieve pressure on overdrawn aquifers and reduce exposure to energy price volatility, while sustaining near-historical production levels and improving reliability under drought. From a policy perspective, the results underscore the need to complement traditional command-and-control allocation rules with planning tools that make explicit the cross-sectoral consequences of irrigation decisions. They also highlight that the credibility and uptake of such tools depend on embedding them in participatory processes with farmers, water managers and energy utilities, as well as on aligning tariff structures, subsidy schemes and infrastructure investments with the incentives revealed by nexus-based optimisation.

4 Conclusion

This study demonstrates that irrigation planning grounded in the water–energy–food nexus can substantially improve the performance of drought-prone agricultural regions, as illustrated by the case of Gansu Province. By embedding hydrological allocation, crop choice, irrigation technology and pumping energy within a unified optimisation framework, the analysis shows that substantial water savings and energy reductions can be achieved without compromising staple grain production or irrigation reliability. The comparison of alternative planning strategies highlights that a narrow focus on either water conservation or energy cost minimisation overlooks important synergies, whereas a nexus-based perspective reveals portfolios that respect environmental flow constraints and relieve pressure on overdrawn aquifers while maintaining near-historical output levels. The findings nonetheless need to be interpreted in light of several limitations. The optimisation model abstracts from intra-seasonal operational complexities, institutional frictions and behavioural responses that may constrain implementation of the identified strategies. Data scarcity and the use of standardised energy factors introduce uncertainty in absolute estimates, even if relative differences between scenarios are robust. Furthermore, the analysis focuses on staple grains and does not fully capture implications for high-value crops, rural livelihoods or ecosystem services beyond environmental flows. Despite these caveats, the results provide a credible basis for integrating nexus-based tools into regional water, energy and agricultural policies. They underline the importance of coordinated planning among irrigation authorities, energy utilities and agricultural agencies, and they point to the need for tariff reforms and incentive schemes that align farmers' decisions with system-wide efficiency gains. Future work should couple the present framework with detailed economic and institutional analyses, test its applicability in other drought-prone regions and explore how digital monitoring and decision-support systems can facilitate adaptive, participatory irrigation planning under growing climatic and resource uncertainties.

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