Journal of Agrometeorology

ISSN : 0972-1665 (print), 2583-2980 (online)
Vol. No. 25 (1) : 61 - 67   (March- 2023)
DOI**:** https://doi.org/10.54386/jam.v25i1.2052
https://journal.agrimetassociation.org/index.php/jam

Invited Articles (Silver Jublee Publication)

Sustainable land-water-food nexus management: Integrated modelling approach

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ABSTRACT

Land, water, and food resources are essential for human survival, economic development, and social stability. Water and land are the basic resources in irrigated agricultural systems. Sustainable agricultural development entails effective management of the land-water-food nexus. The complex relationship in land-water-food nexus, with large uncertainties encompassed therein. Approaches that interconnect Land-Water-Food have grown significantly in scope and intricacy. In evaluating solutions to accomplish Sustainable Development Goals (SDGs) under the contexts of rising demands, resource paucity, and climate change, nexus techniques are helpful. The nexus analysis includes the important interlinkages that could be addressed. In the water-food-land nexus system, optimization approach can increase irrigation water production and optimise the allocation of scarce resources. Model optimisation considers the uncertainties in the systems to help decision-makers devise effective strategies for allocating water and land resources effectively. Integrated modelling with efficient optimization methods aid in solving real-world nexus management issues and provides the results that could serve as the basis for effective management of land-water-food nexus and formulation of agricultural policies.

Keywords: land-water-food nexus, optimisation, resource allocation, sustainable agriculture development

The main causes of the rising demand for water, food, and land include population expansion, fast urbanisation, dietary changes, and economic development. Recently, the burgeoning population and continued economic development have posed significant challenges to water and land resources. The expected increase in the demand for food by 50% and clean water by 30% towards 2030 would further exacerbate water scarcity (Yang *et al*., 2020). The sustainable crop production is a great mainstay for food security, economic growth and social stability in a country. Water scarcity is a major concern for agriculture because water is especially critical for the agriculture sector, which uses about 70% of the total world's freshwater resources (Kang *et al.*, 2017a). According to the Food and Agriculture Organisation (FAO), food production needs to be increased by about 60% than in 2007 to feed the expected global population of nine billion by 2050 (FAO, 2011).

The ever-growing population has led to an increased demand for food and expansion of farmland, which are difficult to be propped physically under the given limited natural resources. With climate and land use change, resource degradation and depletion, rapid population growth and wealth amplification, and faster urbanization, the food supply-demand pressures have been exacerbated by globalization. (Misselhorn *et al.,* 2012). The excessive usage of agricultural resources, the overuse of agricultural inputs, the over-exploitation of groundwater (Brauman *et al.,* 2013; Hashemyv *et al.,* 2018; Kumar *et al.,* 2012), and both internal and external sources of agricultural pollution have increasingly brought prominent problems, all of which considerably challenge sustainable agricultural development (Li *et al.,* 2017). Intensified resource constraints, and limited water and land resources have inflicted major challenges, and the conflicts between sufficient provisions of main agricultural products and resource constraints have become highly acute (Kang *et al.,* 2017b; Mosleh *et al.,* 2017). Confront of global resource shortages, it is necessary to take measures to allocate resources effectively.

There are intricate relationships between the water, the land, and food production, and therefore, also many complex factors need to be considered when seeking to systematically optimise resource allocation. However, previous studies have attempted to consider water as the only important input rather than taking an overall system perspective that also includes the land resources used for agricultural production. Therefore, to integrate the multiple system sectors and resource management to optimise resource

***Article info - DOI*:** https://doi.org/10.54386/jam.v25i1.2052
Received: 01 January 2023; Accepted: 07 January 2023; Published online : 17 February 2023

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allocation, focussing on a nexus approach could be more effective. The multiple causal linkage between water and food production have been a major international research focus. For example, Mortada *et al*. (2018) devised an agricultural policy optimization framework to optimise water and food security under resource and nutrition constraints and attain a sustainable water-food nexus. Ren *et al*. (2018) examined the virtual water flow connections with food imports and exports between Beijing-Tianjin-Hebei and the possibility of mitigating water scarcity utilising a land-water-food nexus. Therefore, the water-food nexus method has been manifested to be effective for quantitatively analysing regional nexus relationships. However, most previous studies have focused on combining field and watershed-level issues, choosing a single input (water), or have deployed a multi-factor approach without considering the watershed issues. To solve multiple input and basin-level problems, it is necessary to systematically and rationally allocate the water and land resources across the whole basin. Water, food, and land are closely related, and water security and food security are interdependent. The relationship can be described as i) food production requires water and land, ii) the land needs water for irrigation, and iii) the generation of green water requires land. Under these conditions, systematic analysis and integrated solutions for the land-water-food nexus are now regarded as one of the most significant and successful holistic strategies for managing resource systems (Niu *et al*., 2019). The sustainable management of the land-water-food nexus can address land use, water use, agricultural system production, and food security (Ren *et al*., 2018; Duan *et al*., 2019). For food security, restructuring the agricultural production through the highly effective use of agricultural water and land resources is greatly desired. Numerous studies (Darshana *et al*., 2012; Li *et al*., 2014; Bas *et al*., 2014; Gephart *et al*., 2016; Jiang *et al*., 2016; Varade *et al*., 2018; Garza-Díaz *et al*., 2019; Li *et al.*, 2019; Niu *et al*., 2016; Elleuch *et al*., 2019; Cheviron *et al*., 2016; Campana *et al*., 2018) have concentrated on the allocation optimization of water, land, and food resources, which primarily utilized optimisation models.

A broad range of optimisation approaches were employed in these research, including linear programming, non-linear programming, multi-objective programming, and mixed-integer programming (Mortada *et al*., 2018; Nie *et al*., 2019; Liu *et al.,* 2019; Li *et al*., 2020; Ren *et al*., 2017; Li *et al.,* 2019; Tang *et al.*, 2019; Linker *et al*., 2016; Dunnett *et al*., 2018) Multi-objective programming (MOP) plays a significant role in managing agricultural water and land resources to support economic and social development and preserve ecological integrity. For instance, Davijani *et al*. (2016) established a multi-objective model to facilitate the allocation of water resources in agricultural in arid regions, considering economic and employment generation factors.

Tan *et al*. (2017) suggested a multi-objective fuzzy-robust programming to facilitate the best use of agricultural land and water resources. A systematic multi-objective optimisation tool proposed by Galan-Martin *et al*. (2017) for optimal cropping patterns maximizing wheat production in Spain while reducing the environmental impact caused due to water consumption. Li *et al*. (2018) presented an interval multi-objective programming model for irrigation water allocation to maintain a balance between economic benefit, crop productivity, and water conservation in irrigation systems. Mortada *et al*. (2018) offered a multi-objective optimisation model for ensuring sustainable water and food security through optimal resource allocation. Nie *et al*. (2019) developed a multi-objective mixed-integer non-linear model for making land allocation decisions under a system of the food-energy-water nexus. Ren *et al.* (2019) formulated an enhanced multi-objective stochastic fuzzy programming method to optimise irrigation water amounts in irrigation areas. A few optimisation models, like IPAPSOM (Lu *et al.,* 2013) and GLOBIOM (Fuss *et al*., 2015) considered water-food interactions and optimised food production under various objectives and constraints.

An integrated modelling approach can address a wide range of nexus questions. A water-footprint-based integrated optimisation model was developed for sustainable management of land-water-food nexus (Chen *et al*., 2020). Blue and green water footprints have been integrated into the model to optimise the allocation and use efficiency of land and water resources within the context of food security objectives and other limitations. The fuzzy fractional programming (FFP) method was created to address ratio optimisation and fuzzy information in model parameters. The integrated model was then employed in the Three Rivers Headwaters region of Northwest China with water scarcity, food deficit, and ecological degradation issues. Yao *et al*. (2021) developed the robust optimization method and demonstrated it in the Yangtze River basin. They found that a robust optimization method could address the uncertainty disturbance and satisfy the target requirements in the context of the water-food-land nexus system. The model could be deployed to similar river basins with limited resources.

LAND-WATER-FOOD NEXUS MANAGEMENT FRAMEWORK

The land-water-food nexus describes dynamic and intricate relationships between water, food, and land. The water system, the food system, and the land system are three interconnected and interacting subsystems that make up the nexus (Fig. 1). The connections between the three sectors indicate linkages, opportunities, and challenges that are more complex. For instance, agricultural development depends on irrigation (blue water) and precipitation, whereas irrigation is influenced by the amount of water that is available. The soil, which provides the crop with nutrients and basic materials, needs underground water. At the same time, crop production supplies grains and other raw materials for food industries. The land-water-food nexus is centred on the crop water footprint. Food security is built on the water system and the land system. Land degradation, changes in runoff, and varied groundwater discharge could all have an impact on agriculture and food production. The challenges in food security, water security, and land security could be mitigated with the help of land-water-food nexus management, which would also encourage effective use of water and land, and fulfil local food demand. An integrated bottom-up model on the management of the land-water-food nexus must be established to tackle these challenges and achieve sustainable development.

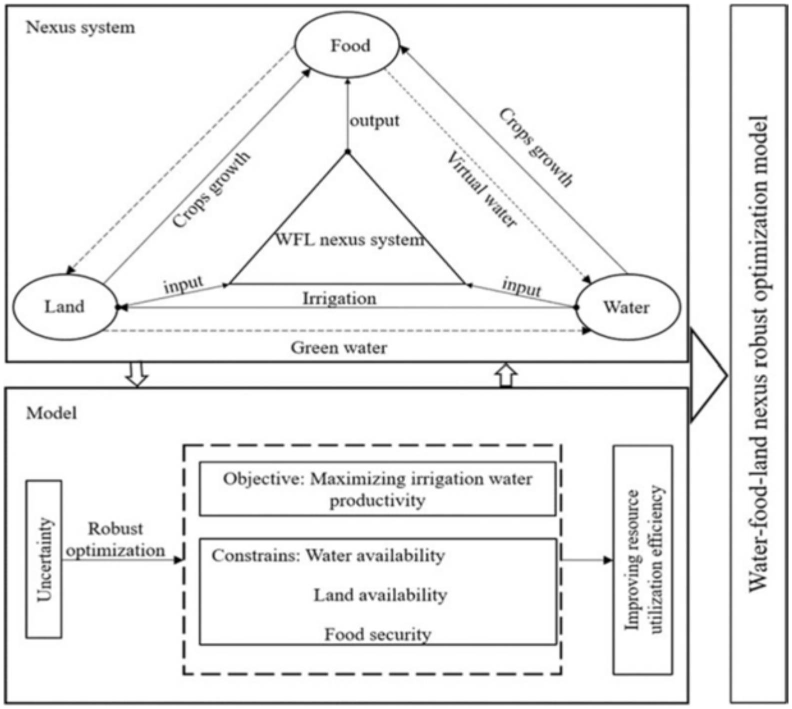

Fig. 1: Land-water-food nexus framework

INTEGRATED MODEL DEVELOPMENT FOR LAND-WATER-FOOD NEXUS MANAGEMENT

Objective function, decision variables, constraints, and solution methods *(Chen et al., 2020)*

i) Objective function: The best water and land resource management plans derive through problem optimisation considering food security and other constraints. One calendar year is the time frame for planning. Decision factors Sij denotes the optimal area cultivated under crop j in sub-region i, which decides the allocation of land and water resources. The model objective is expressed as a ratio of net economic benefit to the blue water footprint, which intends to achieve the net economic benefit with minimized use of agricultural irrigation water (blue water). Hoekstra (2002) estimated the water footprint based on the virtual water (Allan, 1997), which comprises blue and green water footprints. The volume of water evaporating from rainwater stored in the soil as soil moisture (green water resources) is the green water. Blue water is the volume of freshwater water that evaporates from surface and groundwater reservoirs (blue water resources). In irrigated agriculture, blue water is used and it is important to use it prudently with a high level of efficiency. A fuzzy fractional programming optimization (FFOP) model is formulated (Chen *et al*., 2020) as below:

$$\mathrm{Max}\ f = \frac{f_1}{f_2} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\widetilde{P}_j \cdot Y_{ij} - \widetilde{C}_j\right)\cdot S_{ij} - \widetilde{P}_j \cdot T_{ij}}{\sum_{i=1}^{I}\sum_{j=1}^{J} WF_{blueij}\cdot S_{ij}\cdot Y_{ij}}$$

where *i* is the number of administrative region in the study region; *I* is the total number of administrative region; *j* is the index for crop, such as wheat, highland barley, rapeseed, pea, potato, vegetable, and fruit; *J* is the number of crops; *f* is the net economic benefit per unit blue water from cultivation (yuan/m^3); f_1 is net economic benefit (yuan); f_2 is blue water footprint (m^3); S_{ij} is the planting area of crop *j* in region *i* (hm^2); P_{ij} is unit selling price of crop *j*, expressed by fuzzy set (yuan kg^{-1}); C_{ij} is unit cost for planting crop *j*, expressed by fuzzy set (yuan hm^{-2}); Y_{ij} is average unit yield of crop *j* (kg hm^{-2}).

ii) Constraints: The model considers the constraints such as food demand (National/regional annual food requirements), food security (food self-sufficiency ratio), land (total of arable land), water resources (Crop water footprint accounting and crop irrigation water constraints) as well as non-negativity constraints as explained by Chen *et al*. (2020).

iii) Solution method adopted a) transformation of the ratio objective b) transformation of the imprecise objective (Chen *et al*., 2020).

Objective function, decision variables, constraints, and solution methods *(yao ,et al., 2021)*

***i) Objective function*:** The objective function of the model is to optimise irrigation water productivity, with limited resources as the primary constraint. The model objective is expressed as irrigation water productivity by dividing the total grain production in the watershed by the total available irrigation water, which aims to maximize irrigation water productivity (Max f).

$$FP_{ic} = \sum_{i}^{I}\sum_{c}^{C} Y_{ic} \times S_{ic}$$

Where, FP: food production in the region, WA_i: agriculture irrigation water resource allocation in region i ($*10^8$ m^3), i- Subareas, c: type of crops

$$max\ f = \sum_{i}^{I} \sum_{c}^{C} FP_{ic} \Big/ \sum_{i=1}^{I} WA_i$$

Crop irrigation water productivity is described here as the production of grain per cubic meter of irrigation water. The food production is equal to yield per unit area multiplied by planting area [S_{ic} : planting area for crop c in sub-region i ($*10^3$ ha)]

ii) Constraints: Water security, water availability for irrigated agriculture, food security, lower and upper irrigation area limits for each crop (Yao *et al*., (2021).

iii) Solution method: The steps involved in solving the water-food-land nexus robust optimization problem are summarized by Yao *et al*., (2021).

RESOURCE OPTIMISATION

Resource optimization using water footprint-based fuzzy fractional programming

The integrated model (A water footprint-based fuzzy fractional programming: WFFP) was formulated by Min Chen *et al*. (2020) as described in the model development section 3.1.1. It was applied in four regions *viz.*, Yushu, Guoluo, Hainan and Huangnan regions in Three (Yangtze-Yellow-Lantsang) Rivers Headwaters Region (TRHR) of China.

Crop water footprint: The crop water footprint gives the amount of blue and green water consumption and the crop yield per unit area. Larger water footprints of the crop indicate more water consumption during the growth period. There are clear differences in the water footprint of different crops such as Rapeseed (2.007 m^3 kg^{-1}), highland barley (1.230 m^3 kg^{-1}), pea (1.076 m^3 kg^{-1}) and wheat (0.968 m^3 kg^{-1}). The water footprint of potato and vegetables are low with 0.574 m^3 $kg^{-1}$and 0.134 m^3 kg^{-1} respectively. The green water ranged from 72.28% to 81.28% indicating a high ratio of green water use of six types of crops in TRHR. Six crops show the spatial variation of water footprint per unit mass of each crop with different magnitudes. The difference in spatial variation water footprint of six crops is due to the soil type and prevalence of varied climate in Yushu, Guoluo, Hainan and Huangnan regions of TRHR. Through the examination of the spatial differences in the water footprints of various crops, decision support is offered to optimize crop planting and agricultural water resource utilization.

Optimal strategies of crop cultivation reconfiguration: To reduce dependency on imported grain and assure food security, the optimization of water footprint planting structure should be based on meeting local food need first, and the planting area of crops with less water footprint along with greater economic benefits should be optimized. Crop planting area optimization results indicated that compared to the current crop scenario, wheat, highland barley, and rapeseed have a lower economic benefit and a greater water requirement. Therefore, the area planted with these crops is not increased in Yushu, Guoluo, and Huangnan. The area of two low-yielding and high-water-consumption crops, namely highland barley and rapeseed, has been drastically reduced due to grain self-sufficiency in Hainan. As peas and potatoes are with low water requirements and good returns (0.802% and 0.942% million yuan per hectare, respectively), the planting area in Yushu autonomous prefecture grew marginally. As vegetable has the highest productivity (93.46 million yuan per hectare) and the lowest water use, the planting area has expanded slightly in Yushu and significantly in Guoluo.

Economic benefits of 8321 million yuan, 15,737 million yuan, 51,080 million yuan, and 332.02 million yuan can be obtained in Yushu, Guoluo, Hainan, and Huanan, respectively, bringing the total income of the TRHR to 1,083,4 million yuan through optimisation of planting area. Hainan produces a high yield per unit area and a low water footprint of crops owing to its climate and therefore its economic benefits are far greater than those of the other three Tibetan autonomous prefectures. Due to the massive food shortage in Qinghai Province, Yushu, Guoluo, Hainan, and Huangnan must purchase grain at a cost of 24,035 million yuan, 14,852 million yuan, 8,114 million yuan, and 104.12 million yuan, respectively, for a total of 574.13 million yuan in the TRHR.

Crop planting structure modification based on fractional planning and the water footprint theory may save 35% of water resources and boost TRHR productivity by 2%. Taking into account the characteristics and differences of water footprint in crop-planting regions, the advantages of crop planting in different regions can be exploited to optimise the area of crops and irrigation water with a high yield of water savings. Thus, enhances the efficiency of water resource use and the effective use coefficient of farmland irrigation water and reducing the consumption of blue water.

Resource optimisation using robust optimization model

Yao *et al*. (2021) developed a robust optimization model in the water-food-land nexus system for optimising the allocation of limited resources and maximise irrigation water productivity. This optimization model considers all system uncertainties to aid decision-makers in creating more efficient water and land resource allocation strategies. The robust optimization model was used as a solution to a real-world nexus management issue in the Yangtze River basin.

The results of the robust optimization model demonstrated irrigation water productivity of 1.63–1.663 kg m^{-3} in 2019, which was a 3.61%–5.25% increase compared to 2013 (without optimization) and indicated the effectiveness of the water-food-land nexus robust optimization model. Under ideal conditions, the total amount of water allocation to the agricultural sector in 2019 showed a modest increase over the allocation in 2013. The more uncertainty risk is considered, the more conservative the outcomes become. The results indicate that when uncertainty increases, both the total amount of water allocated and the total planting area in the basin decrease. To assure food security, crop planting patterns have been modified to adapt to diminishing water and land resources. Rice and other water-intensive crops have decreased in acreage, but wheat and maize have expanded.

The framework of the robust optimization model for WFL nexus is moveable and applicable to most regions when: (1) the availability of the resources (e.g., water and land resources) was scarce. It is important to reallocate the limited resources sustainably to improve the water use efficiency of irrigation; and (2) the predominant limiting factors (water availability) are highly uncertain. The model outlined the fundamental aims and restrictions for addressing the aforementioned issues (Yao *et al*., 2021).

The model's results analysis contributed to real-world applications and policy implications. As a result of population growth and rapid societal development, resources are becoming increasingly limited. Utilizing resources effectively is the key to sustainable growth. The government should bolster effective management of land and water resources in order to accomplish systematic optimization of resource allocation.

CONCLUSION

Unlike the current approach of crop planning, an integrated (A water footprint-based fuzzy fractional programming: WFFP) model adds crop water footprint into the optimization procedure. Fuzziness associated with crops' produce selling price and production cost are successfully addressed and integrated into the modelling process. WFFP is designed to maximise economic benefits and reduce the blue water footprint in fields with limited water and land resources. WFFP can be effectively implemented in any arid irrigation region which is the most environmentally fragile and water-scarce region in the world. Crop planning and management can be done by WFFP prioritizing the efficient use of agricultural water resources.

The water-food-land nexus robust optimization method can efficiently deal with uncertainty. Robust resource optimization model is capable of optimal allocation of limited water and land resources to various crops in order to maximize irrigation water productivity. It could be utilized in any region to mitigate water scarcity, food crises, and other issues that affect agricultural development. These models are efficient in simultaneously addressing interconnections between water, food, and land subsystems in an irrigated agricultural system. It improves the efficiency of limited resources and provides resource allocation strategies for decision-makers

In addition to land-water-food, energy security should be included in the framework to make the land-water-energy-food (LWEF) nexus. Comprehensive nexus can quantify interconnections among nexus elements, drive for holistic approaches that promote all nexus components, and provide a good platform for testing revolutionary concepts, transformative thinking, and innovation in technology and improved management techniques. Such ingredients are essential to increase overall production efficiency instead of the productivity of different sectors separately.

Incorporating the climate change impact in the integrated model development process of land-water-food nexus management could help in efficiently optimizing resource allocations for achieving sustainable food and water security in changing climate. Climate change induced changes in water availability are expected to affect crop productivity that determines food availability, stability, accessibility and use. This may impair food security, particularly in arid regions. Hence, it is important to explore the impact of future climate change on land-water-food nexus for enhancing food security.

Conflict of Interest Statement: The author(s) declare(s) that there is no conflict of interest.

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