Proceeding Paper

Multistage Stochastic Programming to Support Water Allocation Decision-Making Process in Agriculture: A Literature Review [†]

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Abstract: Water represents a crucial resource to support agricultural production and the world's rising food needs. However, the intervention of various factors intricates the proper water allocation, adding uncertainty and increasing risk in the decision-making process. Multistage stochastic programming (MSP) is a widely used programming technique for supporting water allocation problems governed by uncertainty. Therefore, this study performs a literature review on agricultural water allocation based on MSP, identifying crop yield as the principal farmers' benefits of proper water allocation, four main water allocation problem concerns, and four different uncertain sources. In addition, the study exhibits the advantages of multistage stochastic, interval, and fuzzy programming mixtures to provide better water allocation schemes.

1. Introduction

There is significant pressure for proper irrigation water management planning, since irrigated agriculture is currently the primary user of freshwater worldwide [1,2], and water represents a central input for crop production and agriculture development [3]. However, due to the increase in human activities and user demands, the availability of water resources quality and quantity has decreased [4,5], which causes conflicts between users in various locations worldwide [6–8]. Such situations induce multiple uncertainties that interact and lead to a complex water allocation and scheduling decision-making process. Inexact optimization techniques under uncertainty involve a set of strategies that allow one to face these problems on agricultural water allocation [9]. Multistage programming is a highly used technique that provides stage-structured decision-making schemes for supporting water decision-making based on scenario analysis, modelling uncertain parameters as random variables [10]. MSP establishes an optimization procedure comprising two or more stages. The first stage corresponds to crucial decisions at the beginning of the planning horizon. Other stages incorporate scenario-dependent decisions that let planning corrections reduce the system's total cost [11], allowing proper allocation schemes. Therefore, this work performs a literature review that discloses the primary considerations in water allocation in agriculture and supports a description of agricultural water allocation addressed through MSP, answering the following guiding questions:

1.   What are the implications of proper water resources allocation in improving farmers' benefits?

2.   What are the main challenges faced in the water allocation decision-making process?
3.   What are the main uncertain modelling strategies related to MSP?

2. Material and Methods

This study uses the Scopus and Web of Science databases, since they support exploring and selecting high-impact and peer-reviewed papers with extended coverage [12,13]. The search equation includes three layers. The first and second layers contain stochastic modelling and stage stochastic programming schemes. The third layer includes the study object. The equation avoids the agriculture term, due to its effect of about 78% reduction in the documents obtained. We used a hybrid methodology between Preferred Reporting Items for Systematic Reviews and Meta-Analyzes (PRISMA) and snowball sampling methodology for the final retrieved papers (Figure 1). On 8 October 2021, the search equation retrieved 379 documents, identifying 62 article-type documents in the 2000–2021 timeline through the inclusion-exclusion criteria. The selected articles section follows a concept-matrix review [14], using the three guiding questions' answers.
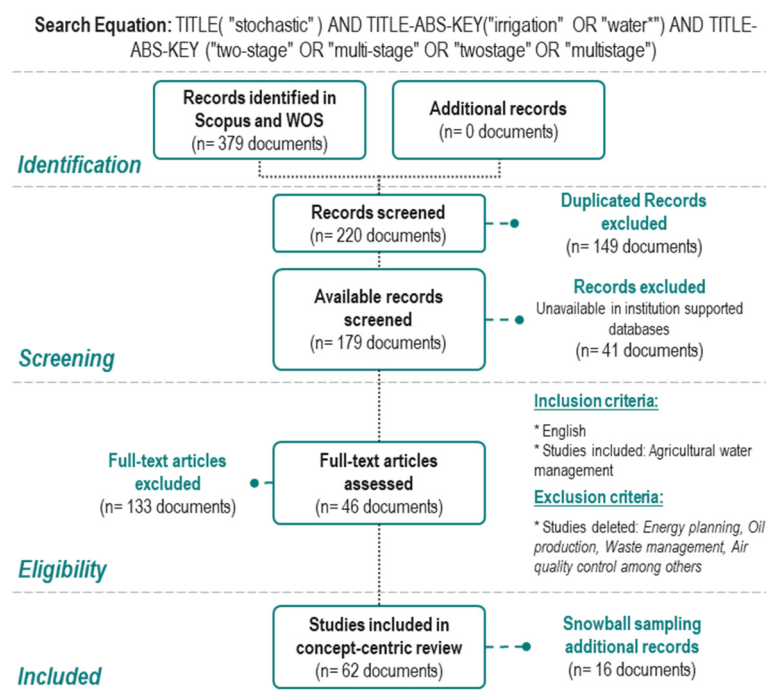

Figure 1. Search equation and flow chart for article extraction.

3. Results

A broad description shows China as the country with the most agricultural water allocation research, probably due to the resource scarcity and the high demand from users in the region [15]. Environmental sciences, engineering, and agricultural sciences comprise the main subareas, grouping 66% of the works. The primary authors related to the problem of water allocation using the MSP technique are Huang G. H, Li Y. P, and Luocks D. P. In addition, Zhang et al. state a categorization for water decision-makers, considering their role in the allocation and their impact on the entire supply chain [16]. 1. The water managers decide the allocation between the primary water users in the region, i.e., industry, municipality, agriculture, and ecological users. 2. The reservoir managers must determine the proper water allocation regarding different zones, farms, districts. 3. The farmers must decide the water distribution strategy among different crops. If the farmers grow more than one crop, they might face a water allocation and scheduling problem, but they might face a water scheduling problem if they grow a single crop [17,18]. For simplicity, in Appendix A, Table A1 contains a summary of the retrieved works.

3.1. First Guiding-Question Answer

The decision-makers' dependency relationship for water allocation establishes a scheme where lower decision-makers' demands ascend to the first decision-maker, which must decide the water quota to fulfil all the requirements. However, each decision-maker seeks different objectives. The first decision-maker pursues the highest system maximum benefit and environmental sustainability. The second decision-maker protects all lower-level users' rights and supports distribution efficiency. Finally, the final decision-makers (farmers) focus on obtaining the most significant benefit possible. Therefore, farmers have the highest risk levels in the system [16]. There are few but significant effects of a proper water allocation plan on the farmer's benefits [9,19–21], regarding that most of the works address the first and second-level decision-makers. Then, an appropriate water allocation of upper levels allows the farmer to achieve the following: 1. To satisfy his water demands primarily and crop yield goals. 2. To prioritize the most flexible crops with maximum net benefits through less water consumption. 3. To plan future production and address proper crop-pattern schemes. 4. To avoid excessive farmers' investments in irrigation and production systems, incurring high costs since a lower water release occur. 5. To promote water-saving and reuse processed water sources. Such implications ensure the agricultural region's development, support the farmer's benefits, maximize the system benefit, assure food, and conserve the natural resources available in the area.

3.2. Second Guiding-Question Answer

Multiple researchers agree that the main problems faced by decision-makers regarding water allocation vary and are inherent to the region where the problem occurs. However, the different case studies highlight the following four main problems: 1. the multiple users' water demands. 2. The available water resources scarcity. 3. The climate change effects. 4. The detriment of the quality of water sources to fulfil water users' needs [20,22–24]. At the same time, these problems are associated to factors governed by uncertainty that are classified into four main classes. The hydrological factors relate to the water cycle and the availability of water resources. Climatic factors are associated with elements that characterize climatic weather. Socio-economic factors link the behaviour of prices and the social environment of the region. The productive factors are related to the productive capacities, production schemes, and decision-makers infrastructure. Hydrological and climatic factors represent the primary uncertain sources in the reviewed works (Figure 2). Water flow levels from available sources are the main uncertain parameter. Such levels are strongly associated with climatic conditions [25,26], implying a critical importance of applying techniques for climatic conditions modelling, which then allows the decision-maker to deduce the availability of future resources. Nevertheless, parameter modelling also lies in the volume of available data, the quality and reliability, and the vagueness and ambiguity [27,28]. Although in different magnitudes, all decision-makers must face these situations to generate proper water allocation plans.
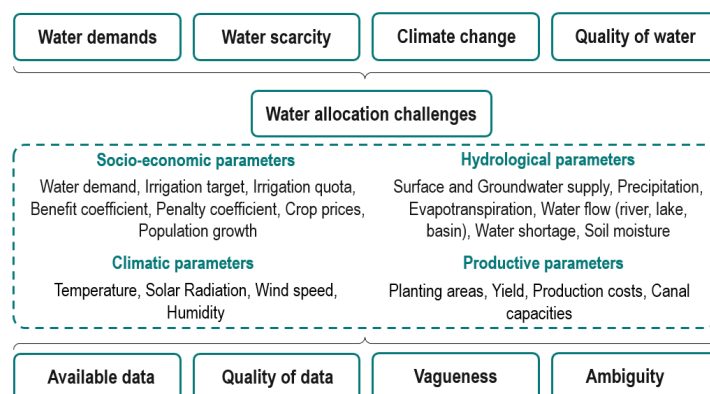

Figure 2. Agricultural water allocation challenges.

3.3. Third Guiding-Question Answer

Proper allocation of water resources at the agricultural level presents complexness that requires careful treatment of the case studies' situations. The problem definition allows for the specifying of aspects of the modelling process as required data, the available strategies for parameters modelling, and the suitable types of mathematical programming for every case study. According to the uncertain parameter modelling strategies used, two programming strategies under uncertainty are linked to MSP, interval parameter programming (IPP) and fuzzy programming (FP). The IPP allows water resource allocation considering intervals to express inherent uncertainty, while FP uses the fuzzy set theory. Each optimization strategy relates to different application situations according to the most suitable method to tackle uncertain parameters. However, due to the complexity of water allocation systems, these techniques have been integrated, exploiting their benefits in reflecting the complexities and multiple uncertainties in the model, allowing for higher and more efficient water allocation schemes [29,30]. Additionally, there are difficulties, such as non-linearity behavior in the model [31] and the number of objectives to fulfil [32], which provide a more reasonably realistic model. Figure 3 summarizes all the optimization techniques used in the studies.
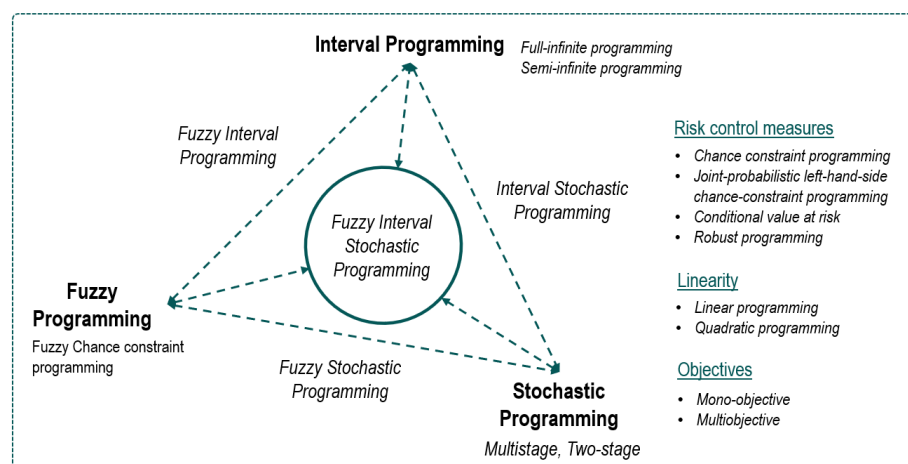

Figure 3. Main strategies related to MSP.

4. Conclusions

This study addresses a literature review to identify the works that use MSP techniques for proper water allocation through an agricultural emphasis. The general findings disclose the complexity of water allocation processes in agriculture, the significant effects of adequate water allocation systems on farmers' benefits, and the matter of implementing advanced modelling techniques that provide suitable water planning schemes. At the same time, the study allows the identification of a less frequent use of MSP techniques aimed at the final decision-maker, without considering the significance of supporting a proper allocation at the farm scale. Even if proper allocation represents reducing water needs at the upper levels, the decrease in errors on setting water requirements, and systems' penalty reductions, more studies should be carried out because this is not a topic under intense research. Therefore, future studies should evaluate the interactions in the crop production processes to define the water requirements, allowing one to scale reliable information to higher levels.

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Appendix A

The Table A1 shows the summary of the selected works according to the decision-maker (i.e., first, second, and third decision-maker), the type of study (Applied Case Studies-ACS and Hypothetical Case Studies-HCS), and the optimization strategy used. If the optimization strategy is mixed (mixed-1: researchers used MSP merged with interval or fuzzy techniques, mixed-2: researchers used MSP merged with interval and fuzzy techniques) or straightforward (i.e., only use MSP techniques).

Table A1. Summary of retrieved works.

Title	Study	DM	Strategy
An interval parameter conditional value-at-risk two-stage stochastic programming model for sustainable regional water allocation under different representative concentration pathways scenarios	ACS	First	Mixed-1
Inexact two-stage stochastic programming for water resources allocation under considering demand uncertainties and response-A case study of Tianjin, China	ACS	First	Mixed-1
An improved inexact two-stage stochastic with downside risk-control programming model for water resource allocation under the dual constraints of water pollution and water scarcity in northern China	ACS	First	Mixed-1
Optimizing water allocation under uncertain system conditions in Alfeios River Basin (Greece), Part A: Two-stage stochastic programming model with deterministic boundary intervals	ACS	First	Mixed-1
A risk-based fuzzy boundary interval two-stage stochastic water resources management programming approach under uncertainty	ACS	First	Mixed-2
Optimizing water allocation under uncertain system conditions for water and agriculture future scenarios in alfeios river basin (Greece)-Part B: Fuzzy-boundary intervals combined with multi-stage stochastic programming model	ACS	First	Mixed-2
A New Interval Two-stage Stochastic Programming with CVaR for Water Resources Management	ACS	First	Mixed-2
An extended two-stage stochastic programming approach for water resources management under uncertainty	ACS	First	Mixed-2
A model integrating the system dynamic model with the risk based two-stage stochastic robust programming model for agricultural-ecological water resources management	ACS	Second	SF
Two-stage stochastic chance-constrained fractional programming model for optimal agricultural cultivation scale in an arid area	ACS	Second	SF
Planning an Agricultural Water Resources Management System. A Two-Stage Stochastic Fractional Programming Model	ACS	Second	SF
A stochastic optimization model for agricultural irrigation water allocation based on the field water cycle	ACS	Second	SF
Stochastic vs deterministic programming in water management: the value of flexibility	ACS	Second	SF
Interval-parameter two-stage stochastic semi-infinite programming: Application to water resources management under uncertainty	ACS	Second	SF
Modeling conjunctive use operations and farm decisions with two-stage stochastic quadratic programming	ACS	Second	SF
An inexact programming method for agricultural irrigation systems under parameter uncertainty	ACS	Second	Mixed-1
Risk assessment of agricultural irrigation water under interval functions	ACS	Second	Mixed-1

Table A1. *Cont.*

Title	Study	DM	Strategy
An inexact stochastic optimization model for agricultural irrigation management with a case study in China	ACS	Second	Mixed-1
Risk aversion-based interval stochastic programming approach for agricultural water management under uncertainty	ACS	Second	Mixed-1
Agricultural Multi-Water Source Allocation Model Based on Interval Two-Stage Stochastic Robust Programming under Uncertainty	ACS	Second	Mixed-1
An inexact two-stage water management model for planning agricultural irrigation under uncertainty	ACS	Second	Mixed-1
Optimization of the irrigation water resources for agricultural sustainability in Tarim River Basin, China	ACS	Second	Mixed-1
A multistage irrigation water allocation model for agricultural land-use planning under uncertainty	ACS	Second	Mixed-1
An interval multistage water allocation model for crop different growth stages under inputs uncertainty	ACS	Second	Mixed-1
Planning seasonal irrigation water allocation based on an interval multiobjective multi-stage stochastic programming approach	ACS	Second	Mixed-1
Risk-based agricultural water allocation under multiple uncertainties	ACS	Second	Mixed-1
Multi-dimensional critical regulation control modes and water optimal allocation for irrigation system in the middle reaches of Heihe River basin, China	ACS	Second	Mixed-1
An inexact CVaR two-stage mixed-integer linear programming approach for agricultural water management under uncertainty considering ecological water requirement	ACS	Second	Mixed-1
An interval multistage joint-probabilistic chance-constrained programming model with left-hand-side randomness for crop area planning under uncertainty	ACS	Second	Mixed-1
Multi-stage stochastic fuzzy random programming for food-water-energy nexus management under uncertainties	ACS	Second	Mixed-1
A nonlinear inexact two-stage management model for agricultural water allocation under uncertainty based on the heihe river water diversion plan	ACS	Second	Mixed-1
An interval-parameter multi-stage stochastic programming model for water resources management under uncertainty	ACS	Second	Mixed-1
A novel two-stage fuzzy stochastic model for water supply management from a water-energy nexus perspective	ACS	Second	Mixed-1
Crop planning and water resource allocation for sustainable development of an irrigation region in China under multiple uncertainties	ACS	Second	Mixed-2
A risk-averse stochastic quadratic model with recourse for supporting irrigation water management in uncertain and nonlinear environments	ACS	Second	Mixed-2
Irrigation water resources optimization with consideration of the regional agro-hydrological process of crop growth and multiple uncertainties	ACS	Second	Mixed-2
Assessment of uncertainty effects on crop planning and irrigation water supply using a Monte Carlo simulation based dual-interval stochastic programming method	ACS	Second	Mixed-2
An improved intuitionistic fuzzy interval two-stage stochastic programming for resources planning management integrating recourse penalty from resources scarcity and surplus	ACS	Second	Mixed-2
An inexact fuzzy parameter two-stage stochastic programming model for irrigation water allocation under uncertainty	ACS	Second	Mixed-2
An interval-parameter fuzzy two-stage stochastic program for water resources management under uncertainty	ACS	Second	Mixed-2
A multi-stage fuzzy stochastic programming method for water resources management with the consideration of ecological water demand	ACS	Second	Mixed-2
Comparison of various stochastic approaches for irrigation scheduling using seasonal climate forecasts	ACS	Third	SF
Stochastic model-based optimization of irrigation scheduling	ACS	Third	SF
Multistage stochastic programming modeling for farmland irrigation management under uncertainty	ACS	Third	SF
A multistage fuzzy-stochastic programming model for supporting sustainable water-resources allocation and management	ACS	Third	SF
CVaR-based factorial stochastic optimization of water resources systems with correlated uncertainties	HCS	First	SF

Table A1. *Cont.*

Title	Study	DM	Strategy
Water resources management under uncertainty: factorial multi-stage stochastic program with chance constraints	HCS	First	Mixed-1
An inexact mixed risk-aversion two-stage stochastic programming model for water resources management under uncertainty	HCS	First	Mixed-1
A risk-based interactive multi-stage stochastic programming approach for water resources planning under dual uncertainties	HCS	First	Mixed-1
Towards sustainable water management in an arid agricultural region: A multi-level multi-objective stochastic approach	HCS	First	Mixed-1
FSWM: A hybrid fuzzy-stochastic water-management model for agricultural sustainability under uncertainty	HCS	First	Mixed-1
Optimal Allocation of Water Resources Using a Two-Stage Stochastic Programming Method with Interval and Fuzzy Parameters	HCS	First	Mixed-1
Inexact multistage stochastic integer programming for water resources management under uncertainty	HCS	First	Mixed-1
An inexact two-stage stochastic programming model for water resources management under uncertainty	HCS	First	Mixed-1
An inventory-theory-based interval-parameter two-stage stochastic programming model for water resources management	HCS	First	Mixed-1
Planning Water Resources Allocation under Multiple Uncertainties Through a Generalized Fuzzy Two-Stage Stochastic Programming Method	HCS	First	Mixed-1
An inventory-theory-based inexact multistage stochastic programming model for water resources management	HCS	First	Mixed-1
The interval copula-measure Me based multi-objective multi-stage stochastic chance-constrained programming for seasonal water resources allocation under uncertainty	HCS	First	Mixed-2
Interactive two-stage stochastic fuzzy programming for water resources management	HCS	First	Mixed-2
ITOM: An interval-parameter two-stage optimization model for stochastic planning of water resources systems	HCS	Second	Mixed-1
Factorial two-Stage irrigation system optimization model	HCS	Second	Mixed-1
Inexact fuzzy-stochastic programming for water resources management under multiple uncertainties	HCS	Second	Mixed-1

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