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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. Besides, the study exhibits the advantages of Multistage Stochastic, Interval, and Fuzzy Programming mixtures to provide better water allocation schemes.

Keywords: Water allocation; Agriculture; Uncertainty; Multistage Stochastic Programming; Interval Programming; Fuzzy Programming; Literature Review.

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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 decrease [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 collect a set of strategies that allow 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 incorporated 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 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 October the 8th, 2021, the search equation retrieves 379 documents identifying 62 article-type documents in the 2000-2021 timeline through inclusion-exclusion criteria. The selected articles section follows a concept-matrix review [14] using the three guiding questions answers.

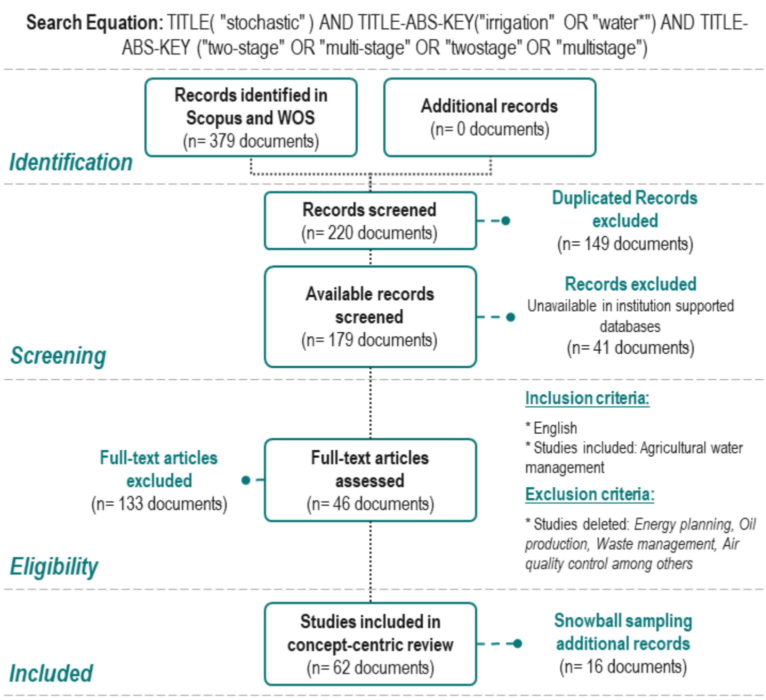

Figure 1. Search equation and flow chart for article extraction

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. Besides, 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, Appendix A the 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]. Considering that most of the works address first and second-level decision-makers, significant effects of proper water allocation plan on the farmer's benefits are rarely with only [9,19–21] retrieved works. Therefore, an appropriate allocation of upper levels allows the farmer: 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 stand out four main problems: 1. The multiples users water demands. 2. The water available 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 associate factors governed by uncertainty classified into four main classes. The hydrological factors relate to the life cycle parameters of water 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. However, these levels are strongly associated with climatic conditions [25,26], implying the criticality importance of applying techniques for climatic conditions modelling, then allows deducing the availability of future resources. Nevertheless, parameters modelling also lies in the volume of data available, 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.

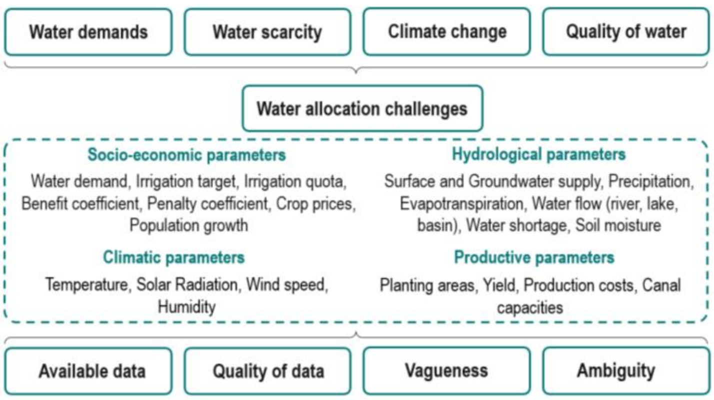

Figure 2. Agricultural water allocation challenges

3.3. Third guiding-question answer

Proper allocation of water resources at the agricultural level presents various complexness that requires careful treatment of the case studies' situations. The problem definition allows specifying 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 parameters 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 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 efficient water allocation schemes [29,30]. Additionally, there are difficulties such as nonlinearity behavior in the model [31] and the number of objectives to fulfil [32] that provide a more reasonably realistic model. Figure 3 summarizes all the optimization techniques used in the studies.

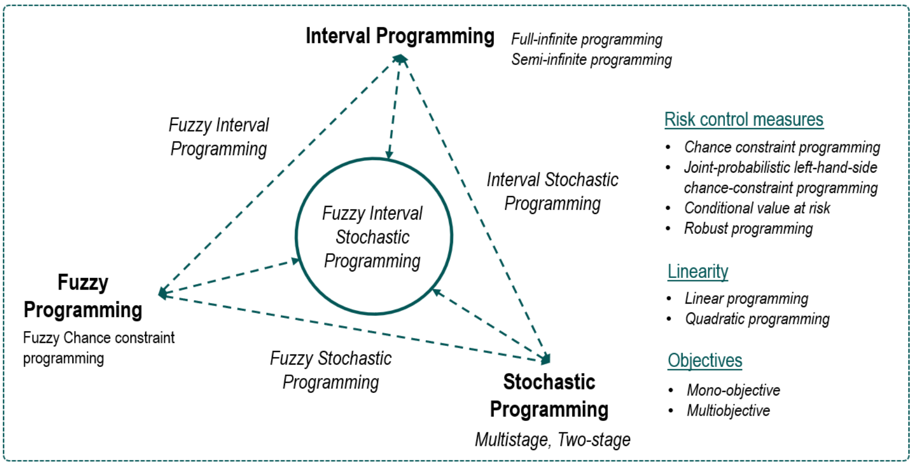

Figure 3. Main strategies related to MSP

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 identifying a less 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 errors decreasing on setting water requirements, and systems penalties reductions, more studies should be done 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 to scale reliable information to higher levels.

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Appendix A

The appendix contains the distribution of the articles selected in the literature review process regarding the decision-maker involved, the type of study, and the optimization strategy used.

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