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Review

Multi-Criteria Decision-Making Methods to Address Water Allocation Problems: A Systematic Review

Sintayehu Legesse Gebre [1,2,*], Dirk Cattrysse [1] and Jos Van Orshoven [3]

[1] Department of Mechanical Engineering, Center for Industrial Management, Traffic & Infrastructure, KU Leuven (University of Leuven), 3001 Leuven, Belgium; dirk.cattrysse@kuleuven.be
[2] Department of Natural Resource Management, Jimma University, P.O. Box 307 Jimma, Ethiopia
[3] Department of Earth and Environmental Sciences, Division of Forest, Nature and Landscape, KU Leuven (University of Leuven), 3001 Leuven, Belgium; jos.vanorshoven@kuleuven.be
* Correspondence: sintayehulegesse@gmail.com or sintayehulegesse.gebre@kuleuven.be

Abstract: The water allocation problem is complex and requires a combination of regulations, policies, and mechanisms to support water management to minimize the risk of shortage among competing users. This paper compiles the application of multi-criteria decision-making (MCDM) related to water allocation. In this regard, this paper aims to identify and to discern the pattern, distribution of study regions, water problem classifications, and decision techniques application for a specific water allocation problem. We applied a systematic literature review study from 2000 to 2019 by using four literature databases (Web of Science, Scopus, Science Direct, and Google Scholar). From 109 papers, 49 publications have been identified and information extracted. This study reveals that in the past two decades the application of MCDM in the area of water allocation has increased particularly after 2014. Around 65% and 12% of study papers were conducted in Asia and Europe, respectively. Water shortage, water use management, and water quality were consecutively the most top-ranked discussed water problems. NSGA II (non-dominated sorting genetic algorithm), GA (genetic algorithm), and LP (linear programming) are the more often applied decision methods to solve water allocation problems. The key findings of this study provide guidelines for future research studies.

Keywords: database; MCDM methods; systematic review; water allocation

Citation: Gebre, S.L.; Cattrysse, D.; Van Orshoven, J. Multi-Criteria Decision-Making Methods to Address Water Allocation Problems: A Systematic Review. *Water* **2021**, *13*, 125. https://doi.org/10.3390/w13020125

Received: 23 November 2020
Accepted: 4 January 2021
Published: 7 January 2021

1. Introduction

Water is an essential resource for the existence of every form of life. It is valuable for maintaining a healthy ecosystem and supporting socio-economic development. The availability of water resources varies in physical state, space, and time. Nearly 75% of the earth's surface is covered by water. However, 97% of the earth's water is found in oceans and seas and is saline. The remaining 3% of the water on earth is freshwater. A large portion (±68.7%) of freshwater is inaccessible to human beings since it is locked up in glaciers, ice caps, and a permanent snow cover in the polar regions. 30.1% is concentrated as groundwater and 0.9% is surface water (2% rivers, 11% swamps, and 87% lakes) [1,2]. Overall, more than 99% of water is unfit and unavailable for human consumption and only 0.0067% of the total water on earth is fresh and accessible for human water use. The rest requires intensive investment to refine for consumption [1]. This shows freshwater is very important and different water uses should be considered very carefully. At a global level, according to the Cassardo and Jones [1]; FAO [3] report, approximately 70% of water is used for agriculture, mainly in the form of irrigation, 22% for industrial purposes, and 8% for domestic purposes and one percent for recreational use.

Water allocation represents the process of distributing water supplies to fulfill the various requirements of water users. The four questions are: who uses water resources, how, when, and where. Moreover, it determines the allocation of water resources to different purposes in space and time. Water allocation influences the economic, ecological, and socio-cultural aspects of an ecosystem. Water allocation is employed to address various water problems. It is applied in a region (areas) where there are competing demands for water by different users. The demand for water use is determined by quantifying the combining sum of the amount of water required with the amount of water available. To avail water resources continuously in space and time, water infrastructures have been built to store water in various parts of the world. These water storage reservoirs are built either for single or multi-purpose use, for example, for water supply, irrigation, and hydropower production.

At this moment, there is a growing competition for water among different stakeholders. In the past decades, global water demand has increased at a rate of about 1% per year as a function of population growth, economic development, and changing consumption patterns [4]. Further, FAO [3] reported that over the last century, global water withdrawal grew 1.7 times faster than the world population.

Hence, this indicates that the demand for water increases the inter-sectoral competition within the nexus of water, food, and energy. In addition, this drives the concern of sustainable water use. Several studies were conducted to address the multifunctional conflicts with regard to the limited water supply. Some studies established and applied water allocation methods to optimally use water resources in a sustainable manner by considering various socio-economic and environmental factors. Multi-criteria decision-making (MCDM) is the most suitable method adopted to solve multi-objective (criteria) water allocation problems. Different computational multi-criteria decision tools have been designed to support decision-makers. It is substantially important to assess the state of the art regarding MCDM for better understanding and application for future research studies.

Previously, a limited number of review studies have been done on MCDM related to water management [5–7]. However, some of the publications were not compiled and did not perform a study in detail, by implementing a systematic review procedure. Moreover, some did not include the recent evolution and distribution of multi-criteria applications across the world. In this study, we review research publications ranging from 2000–2019 on MCDM with regard to water allocation using systematic review procedures by retrieving English based publications from four major literature databases (Web of Science (WoS), Scopus, Science Direct (SD), and Google Scholar (GS)). The objectives of this review study are: (1) to assess the trend of papers based on publication year, (2) to assess the distribution of papers based on the study region, (3) to identify and prioritize water allocation problems, (4) to identify the most frequently applied decision techniques, and (5) to suggest appropriate decision-making methods for different water allocation problems. This review study contains detailed information and useful guidelines for the application of multi-criteria decision-making methods with regard to water allocation problems.

The remainder of this work is organized as follows. Section 2 provides an explanation about the classification of MCDM, Section 3 describes the data and the methodology used, Section 4 presents the results of the review, Section 5 discusses the results in detail, and Section 6 presents the conclusions, limitations, and future research directions.

2. Classification of MCDM Methods

MCDM is one of the most widely used decision methods to perform mathematical optimization in different fields of applications such as water allocation, land allocation, forest management, energy production, project management and environmental protection, and so on [8–11]. The application of MCDM has been an active operational research area for many decades [12]. It is an effective tool used to solve complex and conflicting decision problems. It allows the use of both quantitative and qualitative evaluation factors. MCDM is a generic term used for all methods that are useful to solve complex problems. MCDM methods can be classified into two broad classes MADM (multi-attribute decision-making) and MODM (multiple-objective decision-making) [13,14]. MADM is suitable for selection of a limited number of alternatives and preference ranking. The evaluation is based on predetermined decision alternatives with respect to weighted attributes (i.e., the decision space is discrete). Alternatives are the different choices or preferences available for the decision-maker. These alternatives are assumed to be limited in number or finite. They are supposed to be screened, prioritized, and finally ranked or sorted with respect to the stated criteria decisions or objectives.

There are different types of MADM methods (or discrete MCDM) available such as Value/Utility function (e.g., multi-attribute value theory MAVT, multi-attribute utility theory (MAUT), simple additive weighting SAW) [15,16], pairwise comparison (e.g., analytic hierarchy process (AHP),analytic network process ANP) [17,18], distance-based (e.g., technique for order of preference by similarity to ideal solution (TOPSIS)) [19], outranking (e.g., preference ranking organization method for enrichment evaluation (PROMETHEE),and elimination and choice expressing reality (ELECTREE)) [20–22]. The MODM method is preferably used for continuous optimization problems where the number of alternatives is infinite, i.e., the decision space is continuous [23]. In general, it is suitable for the design of the best alternative planning decision problems in which alternatives are not predetermined but instead, a set of objective functions is optimized subject to a set of constraints. The MODM methods are further grouped into mathematical programming models and heuristic algorithms based on computational time and solution. For example, mathematical methods include linear programming (LP), non-linear programming, mixed integer linear programming NLP, MILP, goal programming (GP), compromise programming CP, and dynamic programming [24]. Heuristic methods include ones such as simulating annealing (SA), genetic algorithm (GA), non-dominated sorting genetic algorithm (NSGA), and tabu search TS [25–27] (Figure 1).

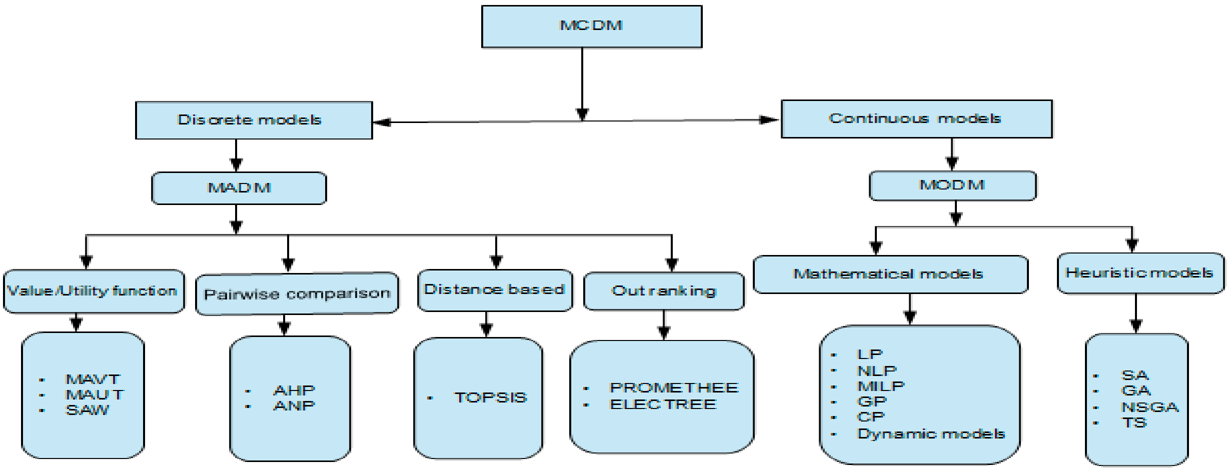

Figure 1. Classification of multi-criteria decision-making (MCDM) methods.

3. Materials and Methods

In this systematic study, all the most acceptable literature web database sources were used. The characteristic feature of each source is clearly stated for better understanding (Table 1).

3.1. Bibliographic Search Engine Databases

1. Web of science core collections (WoS) (https://apps.webofknowledge.com)
2. Science Direct (SD) (http://www.sciencedirect.com)
3. Scopus (http://www.scopus.com)
4. Google Scholar (GS) (http://scholar.google.com)

Table 1. Bibliographic database source characteristics.

Type	Features	What Is Included?	Search Results	Strength	Weakness	Publisher	Year of Data Availability	References
Web of Science (WoS)	Interdisciplinary platform with many databases of sciences. It covers agriculture in the broadest sense, including veterinary medicine	Journal articles, conference proceedings	Reliable sorting. Searches are reproducible and reportable	Ability to analyze search results by author, affiliation, country, journal/book title, and broad subject categories.	Poorer coverage of interdisciplinary journals	Thomson Reuters/ Clarivate Analytics	Established 1973 but data contains since 1900	[28–31]
Science Direct (SD)	Science, technology, and medicine	Journal articles, and books	Reliable and retrievable	Easy to search journal articles and provide full-text access	Low coverage of interdisciplinary sciences	Elsevier	1997	[32]
Scopus	Biomedical sciences, natural sciences, engineering, social sciences, arts, and humanities	Journal articles, conference proceedings	Reliable sorting. Searches are reproducible and reportable	Tools for analyzing search results by author, affiliation, country, journal title, and broad subject categories	Medium coverage of interdisciplinary journals	Elsevier	Launched in 2004 but article indexing coverage goes back to 1970	[29–31,33]
Google Scholar (GS)	All subject areas	Includes all types of documents, e.g., tutorials, posters, presentations	Search results are not reproducible and reportable	International and interdisciplinary coverage (all types of documents)	Few sorting options; many non-peer-reviewed sources	Google	Unknown	[28,29,34]

WoS, Scopus, and SD are the most popular scientific literature search database platforms. They contain a systematic search option that can allow backward and forward search. Further, the databases can easily retrieve a trusted academic journal article. WoS has in-depth coverage of the database compared to Scopus. WoS compiles its database since 1900, whereas Scopus contains scientific literature from 1970 (Table 1). In general, all the above databases cover the wide fields of scientific journals and proceedings [35,36]. These database platforms give more information about the search articles in a more advanced metric system, and the search is reproducible. However, these databases do not inclusively contain all scientific literature for a systematic scientific review evaluation. Therefore, we included the GS database search for our systematic review study because GS adds relevant articles that are not found in the other databases [37]. GS is often used by researchers due to its easy access and retrieves any scholarly journal article records from all web sites [38]. The GS tool has a comprehensive approach in coverage of the scientific and scholarly literature compared to the other database searches [39]. In summary, GS has good coverage of disciplines and multi-languages, particularly in the field of humanities and social science as compared to WoS, SD, and Scopus [30,34,40]. Nevertheless, GS searching is challenging as it lacks the basic functionality of search history, bibliographic metrics, and search interface strategies. This makes that this search strategy is very laborious and time-consuming [41]. Notwithstanding all its limitations, GS can be used in addition to WoS, SD, and Scopus as a search database for systematic scientific literature database sources [42]. In conclusion, each database has its own advantage and disadvantage. Thus, it is advisable to use multiple databases for adequate and efficient coverage [37]. In this systematic review work, all four database sources were used in searching research articles using standard string words on multiple topics under the umbrella of multi-criteria decision-making to solve water allocation problems (Table 2).

3.2. Data Extraction and Procedures

This section presents how data was extracted, archived, and screened for further analysis. The detailed procedure and development are illustrated in Table 2 and Figure 2.

Selecting Research Literature Using Formal Strings

Recently, compared to the informal literature review, a systematic literature review approach is the most adapted practice in the scientific world. It is developed with a formal planned approach to select scientific literature using a string of words that can address and cover the wider topic of research. It is easy to find relevant literature and include quality publications for further data extraction process. The real challenge in a systematic literature review is to define and formulate a search string words. However, this approach helps to assess and validate the review process protocol. A study conducted by Niazi [43] showed that the SLR (systematic literature review) approach outperformed better in collecting the right list of publications compared to the informal literature review method. Therefore, we preferred to use a string words format to select relevant publications. In this study, a wide range of search words were selected and formulated (Table 2). Two important phrases were selected. These were, "water resource allocation" or "optimization", and "multi-criteria decision making of water resource use" or "allocation" then coined with terms, namely, ecosystem service, ecology, agricultural productivity, or environmental management. Finally, the formulated search words were used in the search engine of the web database sources. Table 2 shows the number of hits when inserting those search string words in the search engine in each web database system. The term 'hits' describe the number of publications pop up when the search was done while 'sel' refers to the number of relevant publications selected from the pop-up publications. Only important publications were retained for further screening. Different documents like technical reports, thesis, and other documents were also selected; however, due to duplications we rather left out them and relevant journals were retained. In general, journals are easily accessible and contain summarized results.

Table 2. Scoping results of selected articles based on the four database sources (From 2000–2019, English language-based literature).

		WoS		SD		Scopus		GS		Total
Strings Category	**Strings**	**hits**	**sel**	**hits**	**sel**	**hits**	**sel**	**hits**	**sel**	**sel**
Water–Environment allocation										
W1	TI = ((“Water resource allocation” or “optimization”) and (“ecosystem service”or “ecology”or “agriculture productivity” or“environmental management”))	16	2	57	7	2291	53	2	1	63
W2	TI = ((“Multi criteria decision making of water resource use”or “allocation”) and (“ecosystem service”or “ecology”or “agriculture productivity” or “environmental management”))	17	1	11	1	762	32	171	8	46
Total										109

WoS = Web of Science, SD = Science Direct, GS = Google Scholar, sel = selected, W1, W2 = string category lists, TI = title.

The strings in the case of GS used the same words, but with different word orders to restrict the search engine. In Table 2, the literature was selected using the stated strings from each database through screening of the abstracts, keywords, and titles of the research articles. Eventually, a full-text review has been done to refine the collected articles, and 109 articles were archived for further eligibility assessment. The detailed workflow is presented in Figure 2.

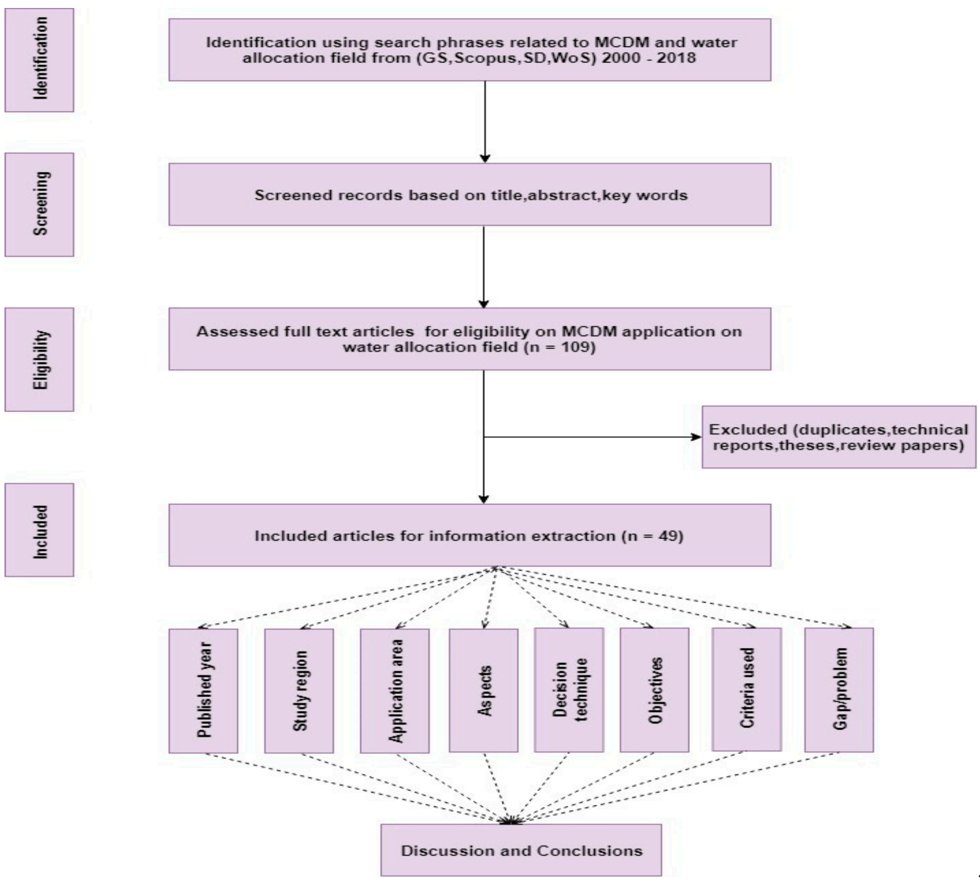

Figure 2. Study flow chart of identification, screening, eligibility, and included articles.

4. Results

In this section, the results of the 49 reviewed publication papers from January 2000 to 2018 are presented. The results are summarized in detail according to: the trend of publications, study region distribution, water problem classification, use of decision techniques, and applications in different water allocation problems.

4.1. Distribution of Research Papers Based on Publication Year

In this study, the trend of published article shows that the evolution of publications increased during the last two decades. Especially after 2014, the number of papers significantly increased. In 2017, eleven publications (22.4%) were released. In 2019, the number of publications also increased. This has been checked and assessed using the search string words. A further increase in the number of publications is to be expected. It also shows the broad acceptance and credibility of the MCDM application to solve water allocation problems [7]. There are different reasons for the growth of publications. The primary factor is due to the paradigm shift in the concept and implementation of water management at the global level. This is accentuated in the adoption of sustainability as an overriding objective in water resources management. The fundamental concept of sustainability progressively becomes a major agenda in the utilization of natural resources after 1992 at the Rio Summit (Earth summit). The issue of sustainability in water resources management planning can be addressed by considering economic, environmental, and social benefits at stake.

Figure 3 shows that the water allocation problem is reasonably expected to remain the center of a research topic. According to Boretti et al. [44] report, the demand for water use is growing at a global level, as a function of population growth, economic development, and changes in consumption patterns. Moreover, the global climate changes are directly affecting the natural pattern of the hydrological (water) cycle. This has undoubtedly contributed to the uneven and erratic water occurrence in various key parts of the world [44]. Therefore, it is necessary to use the available scarce water resources in an efficient and effective way by adopting multi-dimensional perspective approaches. It provides the option to minimize existing and anticipated water problems.

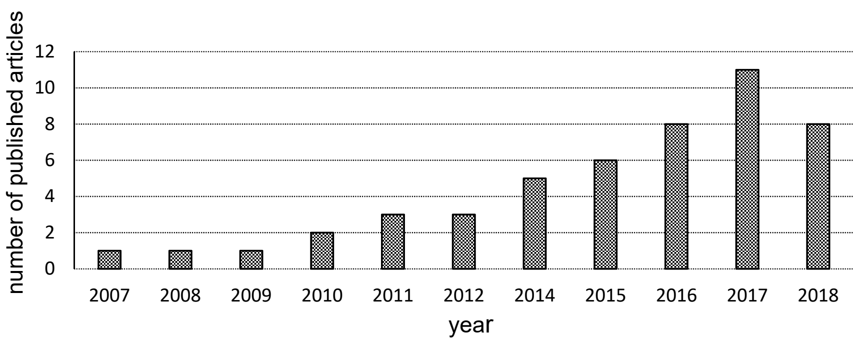

Figure 3. Distribution of the number of published papers based on publication year.

4.2. Distribution of Publications Based on the Study Region

Figure 4 depicts the distribution of MCDM published articles based on the study region. A total of 16 countries contributed to this study analysis and 2 publications were generic (general research study). China accounts for 44.9% (22 publications), Australia and Iran follow by 8.2% (4 publications). It is not surprising that Asia recorded about 65% of the publications, this may be due to a high number of people and it is expected there might be numerous water allocation problems that motivated researchers to engage in multi-criteria tools. Next, Europe (12%) and Australia (8.2%) were the most studied regions. This finding broadly supports the work of other studies on MCDM application on water resource planning and flood risk management [5,7].

Notably, there is a significant water problem in the southern hemisphere of the world associated with drought and untimely occurrence of flooding [45,46]. However, very limited publications have been reported. The rare use of MCDM applications in these continents could be due to a lack of expertise, technology, and resources [5]. In the future, these gaps could be filled by exporting MCDM techniques to developing countries for the implementation of coherent global sustainable water allocation management.

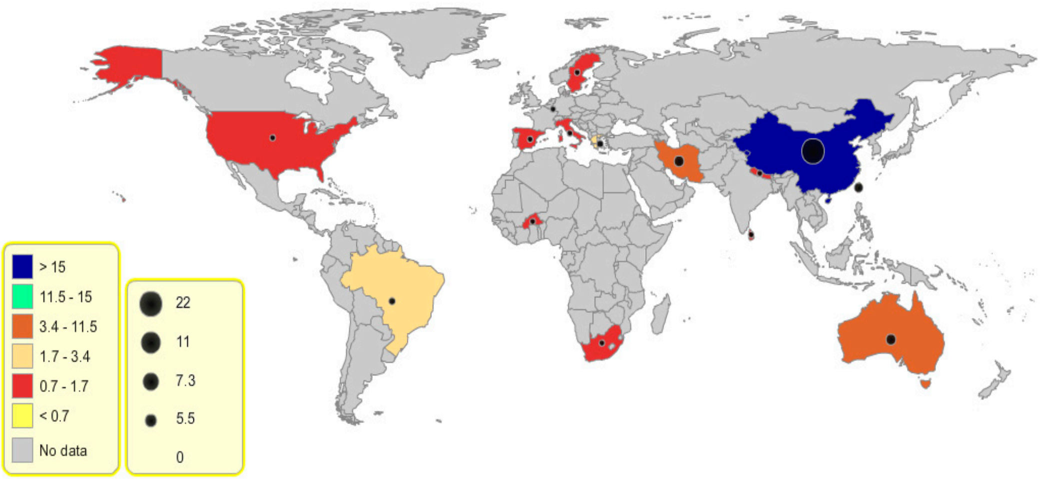

Figure 4. Distribution of publications based on the study region (2000–2018). The color legend shows the range of the number of publications where the dot legend represents the exact number of publications.

4.3. Distribution of Publication Based on Aspects

The primary objective of the application is to maximize the benefits of water use. This implies the achievement of and the response to the growing societal (equity), economic (efficiency), and environmental (soundness) interests. In this review study, the aspects addressed by each reviewed study have been critically identified and analyzed. In most cases, the water allocation problem considers more than one aspect or criterion. Figure 5 shows 47% of the published papers addressed economic and environmental aspects. Thirty-nine percent of the published papers included altogether social, economic, and environmental issues. Only a few studies considered a single aspect, i.e., either the economic or environmental dimension. The reason is, water allocation requires a realistic basis in benefiting the different elements of demand by each user and uses of water. The concept of integrating multi-dimensions in the optimization process of water allocation helps in sustainable conservation and protection of water resources. This idea has emerged into practice after the ministerial declaration of the 2nd World Forum (The Hague, 2000). Water management or water allocation practice has to reflect its economic, environmental, social, and cultural values of all its uses [47]. This study reveals any multi-criteria water allocation study has to consider more than one aspect for the sake of maintaining sustainable water management.

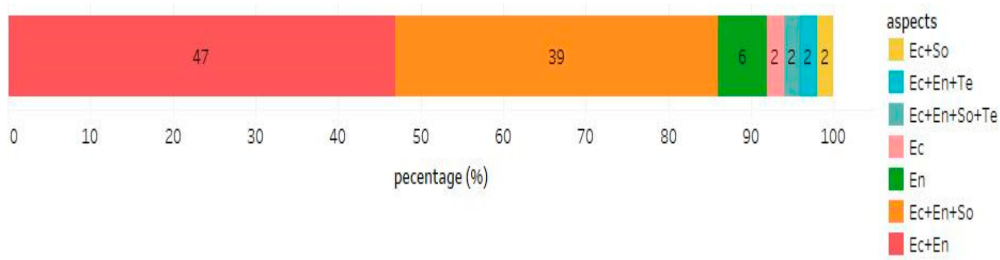

Figure 5. Distribution of publications based on aspect. Ec+So (economical and social); Ec+En+Te (economic, environmental, and technical); Ec+En+So+Te (economic, environmental, social, and technical); Ec (economical); En (environmental); Ec+En (economical and environmental).

4.4. Distribution of Decision Technique Methods Based on Publication Year

Figure 6 presents a comprehensive overview of the trend of decision techniques based on publication year. From the broad MCDM classification, MODM was by far the routine method most applied with 81.6% (40 papers) of the papers, MADM 14.3% (7 papers), and both MODM and MADM in combination was used in 4% (2) of the papers. The study analysis of the different types of decision-making methods used in this review study shows that NSGA (11 times) was the most employed decision method. The second most used method was GA that has been used six times. The third most applied decision method was LP that has been used 5 times. From the multi-attribute decision methods, AHP is the most frequently applied and the top fourth-ranked in the list. Though there were 23 distinctive types of decision techniques discussed, only a few of them were used more than once. Thirteen different types of decision-making methods are used only one time. This indicates MCDM applications in the field of water allocation can be approached by different types of decision technique methods. Nevertheless, the decision method has to be robust that give a reliable solution and with less error. Moreover, it has to be a relevant and regular method that can be adopted and used to address complex problems. Note here, the sum of the decision-making methods (56) does not match with the number of publications (49). Some research articles used more than one type of method. In summary, the result of this study indicates that there is no observable pattern of decision technique used in the last two decades. Surprisingly, even though we used the search from 2000 to 2018, we merely found and included eligible publications since 2007. The classification of the different decision methods as outranking, pairwise, distance-based, and utility function, and so on is presented in Figure 1.

	publication year											
decision technique	2007	2008	2009	2010	2011	2012	2014	2015	2016	2017	2018	Total
NSGA-II						1	1	1		7	1	11
GA					1		1	2	2			6
LP(I)	1								1	1	2	5
AHP				1					1	1	1	4
DM		1			1		1					3
Fuzzy					1						2	3
FUZZY				1				1	1			3
ELECTRE (II)						1					1	2
MIP							1	1				2
SAW						1					1	2
TOPSIS								1			1	2
CCM									1			1
FAHP									1			1
GP										1		1
IQP					1							1
ITSP											1	1
MAUT											1	1
MOABC										1		1
MoBCDM									1			1
Model (DSS)			1									1
MOGM						1						1
PROMETHEE V											1	1
Rule based									1			1
WSM							1					1

Figure 6. Distribution of decision technique type based on publication year. FUZZY = Fuzzy stochastic programming; fuzzy = simply fuzzy method.

4.5. Distribution of Publications Based on Water Problem Classifications

Water is allocated to meet different water users' demands. The water demands arise to respond to, a certain type of water problem, e.g., water shortage, water quality, water ecosystem/environment problem, etc. MCDM is used to address these different water allocation problems. In this study, all the reviewed publications were categorized into seven water problems context-based classification (Figure 7). A detailed explanation of each water problem classification is presented below.

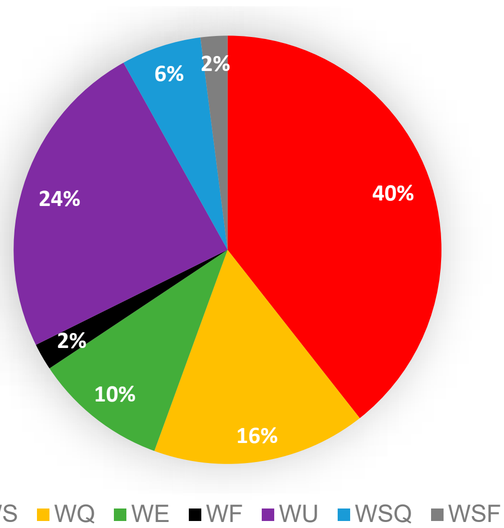

Figure 7. Distribution of publications based on water problem context-based classification. WS (water shortage), WQ (water quality), WE (water-ecosystem/environment), WF (water for flood management), WU (water use planning), WSQ (water shortage-quality), WSF (water shortage-flood management).

Figure 7 shows that 40% (19) of the published papers focused on addressing the water shortage problems. It is the biggest share of publications on water problem context classification. Figure 8 presents the distribution of water problems across study regions. Asia takes a significant portion of the distribution of water shortage problems. China comes first of all countries listed in the review study (20.4%). Taiwan and Iran account for 4% each. In conclusion, the use of MCDM is relevant to solve water allocation problems particularly in high densely populated regions like China. Burek et al. [48] reported that about 73% of people affected by water shortage live in Asia. Australia, Brazil, and Burkina Faso are also some of the countries listed under water shortage problem classifications.

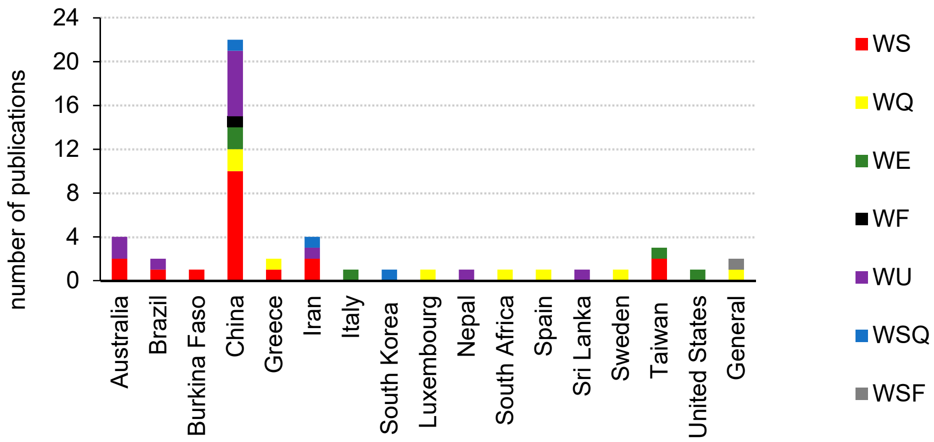

Figure 8. Distribution of publications based on water problems across the study regions.

Next, 24% (12) of the publications used MCDM to solve water use management problems. It is the second hot topic next to the water shortage problem. Some researchers also indicated that the water crisis in the 21st century is much more of water use management than a real crisis in water quantity and quality [49]. Figure 8 indicates, China is the most studied country with 6 publications. The rest of the papers are reports from Australia (2 publications) and one paper each from the countries of Brazil, Iran, Nepal, and Sir Lanka. The reason China becomes the center of water management problem is closely interlinked with high population growth and density (over 30% growth since 1979 and the population is close to 1.3 billion), rapid urban expansion, and economic development (the annual GDP growth rate was 9.8% in the last few years). In addition, China has many graduate researchers and institutional funding opportunities; these might contribute to a high number of publications. Recently, unpredictable climate variability has created and challenged water resources management and planning strategies [50]. According to Reference [51], water use management is a major problem in Central Asia, this is due to its complex nature which is affected by different driving forces at different levels. This report suggests that multi-criteria decision-making will continue to remain an optional technical tool for water resource management problems in the world and in particular in Asia.

In this review study, the water quality problem was the third most covered topic, i.e., 16% with eight publications (Figure 7). Europe (Greece, Luxembourg, Spain, and Sweden) was the most studied region regarding the application of MCDM in the field of water quality problems. China from Asia, and South Africa from Africa, were among the countries listed under water quality problems. In general, developed countries are more likely exposed to water quality problems. As discussed by Martin-Ortega and Berbel [52], there is a possibility of releasing wastes into rivers. Some of the primary sources of pollution are urban, industrial wastewater discharge, agricultural waste discharge, excessive erosion, excessive nutrient waste, and pesticide residue waste runoff from agricultural land. There might be other sources that contribute to water quality deterioration. Furthermore, the concentration level of pollutants is expected to increase by 30% in the near future. In Europe, over the past few decades, nutrient runoff from agricultural areas becomes a problem to coastal sea environments and estuaries which creates eutrophication. Laamanen et al. [53], Rabalais et al. [54], and Zmijewski and Wörman [55] used multi-criteria decision in the Dalälven River (Sweden) to reduce the phosphorous load supplied to downstream aquatic environments. According to a report by the European Environment Agency: State of the Environment Report 2015, around half of the European rivers and lakes have been polluted. For example, the constructed Kiev reservoir in Ukraine has a water quality problem. There is an accumulation of vast suspended forms of minerals and organic matter over the reservoir. About 2–3 million tons of major ions, 30–40 thousand nutrients, and 15 thousand trace elements are accumulated per year [56]. This shows that more multi-criteria-based water quality research would continue to remain the major potential topic in Europe. The problem of water quality study has been reported also in China. This might be due to the economic growth that puts massive pressure on natural resources and waste productions. Several research studies based on the theory of ECK (Environmental Kuznets Curve) indicated how economic growth is important to environmental protection. However, this hypothesis does not work in the case of water pollution in most developed countries. Rather an economic growth creates pressure on water resource quality [57].

Fourthly, 10% (5) publications have focused on the optimization of water allocation to satisfy and protect ecosystem demands. It is the top fourth topic covered (Figure 7). Two publications are reported from China and one paper each from Italy, Taiwan, and the United States of America. In other words, Asia was the most studied continent. This result shows that high population growth and economic development rate in Asia has led to more environmental problems than the rest of the continents. This can create a tremendous extent of ecological and environmental problems even to the river reaches and affecting the aquatic ecosystem. In this regard, Asia′s ecological/environmental management, particularly to water body conditions, will continue to be an important issue [58,59]. In this study report, we found only one publication from China that implemented the MCDM method with reference to water allocation to address flood management problems. With regards to combined water problems, three publications have applied MCDM methods that focused to solve both water shortage and quality problems. All three publications are from Asia (China, Iran, and South Korea). Liu et al. [60] discussed the condition of water problems in China, by considering combined indicators of water quantity and quality over the Huangqihai River basin in Inner Mongolia. The report shows the basin has experienced both problems. However, they stressed that the water quality problem was more serious than the water quantity problem. With the increase of socio-economic growth, Satoh et al. [61] projected that by the 2050s, water demand in Asia will be larger than the sum demand of all the other continents together. In general, in the future, water quantity and quality problems will be an upfront challenge in Asia's water resources management. Similarly, only one generic study employed multi-criteria decision-making to address combined water allocation problems of water shortage and flood risk minimization (Figure 8). This paper used fictitious data to run and produce an optimized solution to address multi-objective functions.

4.6. Description of Water Problems and MCDM Methods Application to Solve Water Resource Allocation Problems

4.6.1. MCDM Methods Application to Solve Water Shortage Problems

Water shortage happens when the demand for water use exceeds the supply of water resources in a certain geographical location over a certain time span. The concepts of shortage or scarcity are relative terms. There are quite a number of definitions of water scarcity or shortage. However, there are a few that stand out as robust and well-constructed. In this part, it is not our intention to review all those definitions but to provide an overview of the meaning of what it does refer to. According to FAO [62], it is a concept of describing the relation between demand for water and its availability. It is obvious also that demand and availability are comparative. It varies from place to place, seasons, and local climatic conditions. Water shortage or scarcity is classified into two broad categories i.e., physical scarcity and economic scarcity. Physical scarcity refers to scarcity in availability due to a physical shortage of water resources in a given region. Economic scarcity describes water access due to a lack of adequate infrastructure and institutions to ensure regular water supply [63]. There have been many strategies developed in order to compact water shortage by constructing water resources development structures in different parts of the world. Many researchers have used MCDM in water allocation problems to address the water shortage. Water shortage is the major water allocation problem. Water scarcity is the world's most challenging problem, Mekonnen and Hoekstra [63] stated about 4 billion people, nearly two-thirds of the world population, experience severe water scarcity at least one month per year. Which is about 66 percent of the world's population. Almost half of those people reside in India and China. This could increase to some 4.8–5.7 billion in 2050 [48]. The water shortage problem will continue to be a great challenge in the future. Therefore, to address complex multi-objective water shortage problems, it is recommended to use and apply decision-making methods.

In this section, 16 publications used MODM methods, 2 papers applied MADM, and one paper employed both methods to solve water shortage problems. From the heuristic decision methods, NSGA II and GA were predominantly used by 7 publications. The NSGA II decision method was the most frequently used method. The NSGA II method was applied by Uen et al. [64] on the pivotal Shihmen Reservoir, Taiwan, to address the water shortage problem. They reported that short-term reservoir operation outcomes from the NSGA II methods increased hydropower production but only slightly affected water supply to the different stakeholders. Actually, their results were based on a short-term plan. Similarly, Zhang et al. [65] employed the technique on the Dahuofang Reservoir, Hunhe River, China, to optimize the trade-off changes and to minimize water shortage. Chu et al. [66] used NSGA II on the inter-basin connected reservoirs called Dahuofang, Guanyinge, and Shenwo in China. The other type of heuristic method used was GA. This technique is discussed in four publications. For instance, Xu, Q et al. [67] applied GA to the Heihe River Basin, China, to reduce the water shortage for the different stakeholders. Hu et al. [68] implemented GA in the Qujiang River basin China. Lai [69] used GA to solve the water shortage in China. Fowe et al. [70] applied a GA to address irrigation water shortage on the Boura reservoir, Burkina Faso.

Like heuristic methods, a number of different types of mathematical models are used to address water shortage allocation problems. For instance, interactive two-stage fuzzy stochastic programming (ITFSP) is used by Niu et al. [71] in a case study on the Hetao irrigation district, one of the largest irrigation districts for food production in China. They considered irrigation benefits, economic penalty, and irrigation quota as constraints to maximize agricultural system benefits through allocating the limited water to three main crops (i.e., wheat, maize, and oil plant). A dynamic model is implemented by Wang et al. [72] for optimal water distribution on the Heihe River Basin in the northwest of China and by Grafton et al. [73] on the Murray River of Australia. They used optimal quotas, drought status, weather condition, and storage status as criteria to maximize the net present value of water between extractions and in situ uses. Elmahdi and McFarlane [74] tested an integrated decision support system (DSS) on the Gnangara Groundwater System (GGS). That is a large aquifer situated in the southwest region of Western Australia. Their research employed different models together to maximizing recharge, maximizing biodiversity, maximizing short-term economic gains, maximizing food security, maintain zero abstraction for public water supply by considering quantitative indicators namely environment (e.g., climate, land uses, land management, status of river gauge or river reach) and socio-economic factors (e.g., policies). A MILP decision method was used by Roozbahani et al. [75] to solve transboundary water allocation problems to reduce water shortage to different stakeholders in the Sefidrud Basin, Iran. Later, they extended their work by introducing additional constraints that maximize the minimum water allocation ratio to the stakeholders [76]. Other types of mathematical models such as rule-based, inexact quadratic programming (IQP) and multi-objective based sum weighted method were used to solve water shortage problems by Song et al. [77], Cai et al. [78] and Shang [79], respectively.

In this segment, the multi-attribute decision method was rarely used. Alamanos et al. [80] employed four types of methods and compared their results, namely, multi-attribute utility theory (MAUT), analytic hierarchy process (AHP), elimination and choice expressing reality (ELECTRE), and technique for order of preference by similarity to ideal solution (TOPSIS). They optimized the water allocation problem of the Lake on Karla Watershed, located in central Greece. Lee M et al. [81] used a multi-attribute weighted method to minimize sever water shortage from excessive irrigation use of the Choshui river, Taiwan. One publication used both multi-attribute and multi-objective methods for feasible actions (alternatives) that can balance water supply-demand in the semi-arid region of northeast Brazil, i.e., PROMETHEE V and Integer linear programming (ILP) [82].

4.6.2. MCDM Methods Application to Solve Water Use Management Problems

Water use refers to the total amount of use of water by the ecosystem, for domestic purposes and agriculture, for energy production, and by industrial sectors [3,83]. It is essential to measure and evaluate the amount of water used by these different users. This leads to water use management. Water use management is defined as a process of planning, developing, distributing, allocating, and managing the optimum use of water resources [84]. Water use management endures the idea of optimum allocation of water resources by taking into account ecological, economic (including water price), and social functions [83]. In summary, water use allocation consists of a combination of policies, laws, and mechanisms to manage the distribution of water resources among competing uses. Modern water use management strategies should be robust by performing well under both average and extreme conditions. Moreover, it should be flexible and adjust to changing conditions over a time span [85]. At present, the issues of water resources management are addressed by considerations of any sectoral interference and trade-off [86]. This paradigm shift in water resources management is precisely the requirement of equitable distribution of water among users, the need for adequate governance, efficient and effective economic measures, and environmental performance. Optimal water use management is one of the fundamental objectives of water allocation research studies.

In this topic, 10 reviewed publications fall under multi-objective and one paper is categorized under a multi-attribute decision-making method, and one paper uses both methods. From the MODM class, the heuristic method NSGA II is the most predominantly employed decision method. Five publications use NSGA II to solve water use management problems. Hurford, Huskova, and Harou [87] applied the NSGA II method to generate optimal water management options that consider the benefits of all stakeholders on a multi-reservoir water system located on the Jaguaribe River, Brazil. They suggest optimum water use policies that incorporate economic, ecological, and livelihood dimensions. The results show an increase in allocated water to different downstream users. A similar decision technique method is used by Dai et al. [88]. They propose an optimal reservoir operation on the Three Gorges-Gezhouba cascade reservoirs in China. The proposed water management option will enable decision-makers to establish suitable reservoir operation rules. They come to the conclusion that NSGA II is an effective and recommendable method to optimize especially reservoir operations. The procedure is fast, flexible, and easy to accelerate sorting processes and compares individuals in a population [89]. The NGSA II method has an improved computational complexity convergence efficiency and model robustness [89]. Lewis and Randall [90] applied the technique to manage water for crop production at the Murrumbidgee irrigation area in Australia. They consider different constraints (i.e., available water, cultivated area, environmental flow, and groundwater pumping rate) to maximize net revenue, minimize groundwater pumping, and minimize variable costs. The result presented optimal water use for different crops under different scenarios that allocate land for each crop to maintain sustainability. Martin et al. [91] implemented NGSA II on the Goulburn-Broken River catchment, Victoria, Australia, to manage water distribution to different users. Yan et al. [92] employed the same method to identify and assess a robust water allocation plan for future water use of the Pearl River basin. Furthermore, different types of mathematical models are implemented to solve water use management problems, e.g., a multi-stage fuzzy stochastic programming (MFSP) is applied by Li C et al. [93] to solve complex water resource management problems in the northwest of China. Goal programming is applied by Li Yet al. [94] on the South-to-North Water Diversion Project in China; LP [95] is employed to analyze the trade-offs in the water–energy—food nexus in Nepal and compound cloud model (CCM) to solve a water allocation problem in Nanjing [96]. In addition, a hybrid of TLFWM (mathematical model) and STLFCWM (mathematical model) is applied by Li M et al. [97] to allocate the limited water resources to different water users in the Northwest of China. Moreover, the STLFCWM model has a unique advantage over a TLFWM model since it addresses random uncertainty in the form of a membership function. The model can provide optimal water allocation plans under different flow levels. Another paper by Rousta and Araghinejad [98] used both MODM (Ideal point distance-based methods _TOPSIS) and MADM (SAW) methods to address water resources management of the Gorganrud River Basin in the north of Iran. In this part, only a single paper used the multi-attribute AHP technique to select the best reservoir to achieve sustainable water use for aquaculture development in Sri Lanka [99].

4.6.3. MCDM Method Applications to Solve Water Quality Problems

Water quality is defined as the condition of the water content with reference to the physical, chemical, and biological characteristics. It is expressed as the suitability of water for particular purposes like drinking, swimming, agriculture, and industrial demands [100]. The water quality is measured by analyzing many factors such as the concentration of dissolved oxygen (DO), salinity (TDS), heavy metals, nutrients, phosphorus, nitrate, ammonia, microorganisms, PH, water temperature, and the amount of suspended materials in the water (turbidity), etc. [101].Water quality level is determined by measuring the chemical and physical contents and then it has to be compared with the global standard. The water quality level ranges vary depending on the intended water use. The quality of water required for municipality purposes is different than the water quality level needed for industrial or agricultural activities. Good quality of water is crucial and required for humans, animals, and the environment. On the other hand, poor quality of water creates health risks and negatively affects the ecosystems. Water quality is significantly affected by wide ranges of natural and human influences. Natural factors that arise from geological, hydrological, and climatic conditions affect the quality of water. The amount and degree of influence are largely visible in the case of arid and coastal areas. Negative humans' activities on top of environmental pollution enact a considerable role in deteriorating the water quality [102]. Wastes (pollution) from human activities (e.g., domestic, agricultural, industrial inputs) are the key reason for water quality decline in various parts of the world. Currently, human activity pollution constitutes a critical threat to water quality. For instance, when wastes from human activities are dumped into water sources (e.g., lakes, rivers), then water sources are polluted. This means it is contaminated by foreign substances so-called pollutants. These pollutants change the water use suitability, and it is harmful to organisms and the environment [103–105]. In general, the water quality status of a given water resource is assessed by thoroughly measuring and summarizing the data, then it is reported in the form of a water quality index (WQI). The water quality index represents a summary tool for reporting evaluated water quality conditions in numeric expression in an understandable manner to the public and decision-makers [106]. Many studies have implemented MCDM methods to minimize water quality problems in water allocation planning by considering conflicting multi-criteria.

With regard to water quality problems, 2 papers applied the MADM and 6 publications applied the MODM methods. From the MADM method class, both papers used AHP decision techniques. The AHP used by Martin-Ortega and Berbel [52] had as a target to find the best criteria (attribute) from the trade-offs between the attributes involved by a number of respondents. This would help to identify the best environmental benefits in the context of EU Water Framework Directives to improve the water quality of the Guadalquivir River which is located in the southern part of Spain. The other study by Li Y et al. [107] adapted AHP to select the optimum site for industrial wastewater discharge at the Luoyuan Bay coastal area in Fujian of China. The study aimed to provide alternative sites to minimize the threats of pollutants coming from industry discharges. With respect to the MODM method classification, 3 publications employed a heuristic type of decision methods like (e.g., NSGA II and bee colony) and 3 papers used mathematical models such as LP, inexact two-stage stochastic programming (ITSP), and a Fuzzy approach. Raei et al. [108] applied NSGA II on a hypothetical area to design an optimal in situ groundwater bioremediation system. NSGA was also used by Zmijewski and Wörman [55] to optimize the tradeoff between hydropower production and reduction of the transport of phosphorus in the reservoir network of the Dalälven River, Sweden. Another form of heuristic algorithm method called Multi-Objective Artificial Bee Colony-based optimization approach (MOABC) was applied to allocate water quality monitoring stations in the Great Fish River, South Africa [109]. They reported, the method performed well under the considered criteria for building water quality networks along the river basin. In their report, they suggested the MOBAC algorithm for further use in the field of water quality. This is because, MOABC is based on the principle of swarm-intelligence, searching the global optimal by escaping from local optima. It is a very useful method for the exploitation and exploration of these types of problems. One publication by Karterakis et al. [110] utilized a hybrid method by combining a mathematical LP and a heuristic method called differential evolution (DE). The aim of the paper was to develop an optimal groundwater pumping scheme that supplies adequate freshwater demand in coastal areas of the karstic aquifer in Crere, Greece, without deteriorating the quality of freshwater due to the seawater intrusion. Regneri et al. [111] applied fuzzy programming to solve the combined sewer overflow problem to the Haute-Sûre storage lake in Luxembourg. Furthermore, mathematical models like ITSP (inexact two-stage stochastic programming) were employed on the Yinema River basin in northeast China [112]. They reported that optimal water allocation strategies to the four water sectors would improve the water use and water quality in the Yinema River basin. The study suggested the ITSP approach as applicable and effective for the management of water resources and limiting water pollutants. However, this model did not consider decision risk uncertainties, different water sources, climate change influence on water availability, and wastewater treatment efficiency.

4.6.4. MCDM Methods Application to Solve Water Ecosystem Problems

Ecosystems consist of four primary components namely water, land (soil and rock), air, and biological organisms (plants and animals including humans). An ecosystem is interrelated and the interaction is complex. Forests, wetlands, and grasslands ecosystems play a role in the global hydrological cycle. The normal functioning of the ecosystem components is immensely important for the water cycle and essential for achieving sustainable water management. Water is a notable part of an ecosystem. The aquatic/water ecosystem refers to the water-based environment in which plants and animals interact with the non-living features of the water-based environment system [113]. A water ecosystem serves to replenish and purify water resources. It is very important for human and environmental well-being. However, the sustainability of the water ecosystem has been affected by human activities like agricultural expansion, deforestation, degrading wetland, marsh areas, and effluent discharges from industries and households to water bodies [114]. This has a negative impact on the natural hydrological (water) cycle and can pollute surface and groundwater resources. To overcome such embedded problems, an ecosystem management approach has been introduced. The ecosystem management approach has received strong attention at the international level after the concept of natural resources management came into the agenda of the United Nation Environmental Program. Ecosystem management represents an integrated approach to managing the healthy functioning of the diversified natural system to ensure the sustainability of ecosystem goods and services to human beings′ needs [115]. Ecosystem services and goods include necessary benefits for societal interest, i.e., allocation of energy production, clean air, and maintaining the nutrient cycle, and operational of the water cycle. Some studies estimated that 64% of the world′s wetlands have disappeared since 1990 and the percentage of loss is higher in Asia [116]. According to Reference [113], on a global scale, ecosystem services from wetlands are in decline in terms of the services they provide. From 1997–2011, between 4.3 USD and 20.2 USD, trillion per year worth of ecosystem services were lost due to land-use change [113]. Currently, a paradigm shift has taken place in recognizing ecosystem management as an integral part of integrated water resources management to more sustainable aquatic development [117]. Multi-criteria decision-making methods have been used to allocate water resources to maintain and sustain ecosystem services.

In this regard, all 5 publications adapted the multi-objective decision-making (MODM) method. Three papers used a heuristic algorithm (GA, GA, and NSGA II), and the other two employed mathematical models (dynamic programming and MOGM).Yang [118] developed a genetic algorithm to optimize water allocation from the Yellow River Delta, China, to meet the environmental flow requirement of the restored wetlands. The model result of water release coincides better with the ideal value plant community needs. The GA model is best suited and effective to optimize water distribution for ecosystem/ecological problems. GA was used by Akhbari and Grigg [119] to optimize water allocation from the San Joaquin River, California, USA, to satisfy the environmental needs of the surrounding region. They reported the GA model performed well in producing an optimal solution. The sensitive results are appreciated and accepted. Cioffi and Gallerano [120] studied the Pieve di Cadore reservoir (Piave River, Italy), using two different optimization methods to optimize water release for power production and fish habitat protection (aquatic ecosystem). They compared and analyzed the performance of the two models′ observational results, i.e., e-constraint and NSGA. The e-constraint method was first introduced by Haimes et al. [121].It keeps one of the objective functions to be optimized while the other objective functions are converted into constraints by setting an upper bound to each of them [121]. The e-constraint method is faster computationally and allows a direct sensitivity analysis of the solutions under constraints. On the other hand, the NSGA method is by far more informative than an e-constraint method (traditional method). Besides, it provides an option to examine the intermediate results of the optimization solution space.

Mathematical models are also often used to address the water problem with regard to ecological/ecosystem management. Lee [122] studied how to optimize the environmental and economic demands on the Tseng-Wen reservoir, Taiwan. He used the multi-objective game-theory model (MOGM) and e-constraint methods to analyze the conflicting interaction between economic development and environmental protection. They reported that MOGM is preferably used for environmental problems because it supports and permits a more realistic simulation of stakeholders' preferences. Moreover, the model is suitable for providing a general planning and policy insight. Whereas, the e-constraint method focuses on either minimization or maximization of a specific environmental factor/objective of an optimization problem. Furthermore, sometimes the results of the traditional multi-objective optimization may not be feasible or socially acceptable. This leads to a failure to implement the strategy or policy. On the contrary, MOGM is flexible to find politically and socially acceptable compromises [123]. In general, with MOGM it is easier to incorporate socially sound choices for policymakers to realize into practice. The other type of mathematical models, called Feasible search discrete differential dynamic programming (FS-DDDP), was used to optimize reoperation of multi reservoirs for integrated water management to address the conflict interaction between water use and environmental deterioration of Nanpan River, China [124]. The results of the study showed that the model performs well in the optimal reservoir reoperation problem compared to routine reservoir operations. They suggested the model can be readily extended and applied to multi-reservoir water management systems.

4.6.5. MCDM Methods Application to Solve Flood Risk Problems

Flood is defined as an overflow of water that submerges land areas that are usually dry [125]. Flood originates from various sources like oceans, seas or rivers, and lakes. Flood is normally triggered by extreme rainfall events or heavy precipitation, e.g., by monsoon rains in Asia and the Indian peninsula, and snow melts due to rapid temperature increases (example in Northern hemisphere during spring season after strong winter snowfall, this occurs when the season changes from winter to spring, it results in a slight temperature change) which causes an increase in river flows and elevation. Further, a flood also occurs when intensive long-duration rainfall happens during autumn that is when summer ends. A flood occurs when manmade dams fail due to many unpredictable causes like landslides, technical errors, or volcanic eruptions and earthquakes. Recently, flooding has remained a recurrent phenomenon in coastal and estuarine sea areas of the world due to extreme atmospheric depressions (e.g., cyclones, typhoons, and hurricanes). Flooding results also from sea level rise and natural events of an earthquake volcanic eruption (e.g., tsunami tidal waves) which causes massive volume of water displacement from oceans or sea to land areas [125]. Flood has a negative impact on infrastructures, damaging homes, community and agricultural production, and natural biodiversity. Moreover, it might risk human health if the water is exposed to pollutants. The extent and the magnitude of the impact depend on the nature and occurrence of the flood in a given region. Flood management includes both operational and administrative activities that have been taken before, during, or after the occurrence of flood events to mitigate or prevent flood impacts on the socio-economic and environmental resources. As part of flood operational management, reservoir water allocation is considered a flood controlling mechanism. Flood is one of the worst natural hazards affecting the life of people. For example, between 2000–2014, more than 85,000 human fatalities occurred and affected about 1.4 billion people around the globe [5]. Therefore, flood risk management is important and it requires the use of multi-criteria decision-making methods that consider multiple objectives, constraints, trade-offs, and feasible alternatives.

This section point out the evaluation of an MCDM application specifically aimed at flood release control of reservoirs. Extreme events of river flow and high reservoir storage result in an overflow of water and have negative consequences on wealth and human beings if a flood disaster occurs. It is important to minimize and mitigate the impacts of the flood by controlling reservoir operations and regulating the river flow. However, reservoir flood operations, especially cascade reservoirs, are complex and challenging for water resources planners and decision-makers. Hence, the objectives of flood operation in the case of multi-reservoir systems are complex, due to conflicting interests among different objectives. For example, water releases from a reservoir may be required to maximize hydropower generation, at the same time as releases need to be restricted to minimize flooding at downstream river reaches. Jia et al. [126] adapted and implemented the multi-objective best compromise decision model called (MoBCDM) on the Shiguan River basin (consists of two reservoirs, three flood control points, and two flood routing river reaches) to improve the optimal flood operation practices of frequently changing the opening of flood gates in central China. The model is composed of a utility function for a quantitative preference comparison, fuzzy analytic hierarchy process (FAHP) for assigning weights, DE for an optimization algorithm, and segmentation and averaging Seg/Ave for a feasible floodgate operation. They considered four historical flood operations scenarios to test the model. The results prove, the MoBCDM outperforms well in all reservoir operation scenarios in reducing peak flow at flood control points when validated to the observed reservoir rule operation. Moreover, this model has interacting features in considering decision-makers′ preference information. However, the flexibility and efficiency of the model have not been tested when the system dimensions size increases like when a number of reservoir and control points increases. The detailed criteria and objectives list used in the model analysis are presented in Supplementary Material Table S1.

4.6.6. MCDM Methods Application to Solve Combined Water Problems

Water Shortage and Water Quality Problems

MCDM has been extensively applied to support decision-making processes for issues related to water quantity and quality. Multi-criteria decision tools are preferably applied to address combined water problems. It is an effective tool and especially after mid-20th century, MCDM has been successfully used to select optimal strategies to reduce water shortage and water quality problems, supporting to optimize the allocation of water resources [127]. In recent decades, water quantity and quality problems represent a hot topic agenda. WHO [128] reported that more wastewater is generated and dispersed today than ever in the history of our planet. Around 1.1 billion people lack access to safe drinking water and 1.8 million people die from diarrheal disease each year. Water allocation to solve water shortage and water quality problems is essential for decision-makers because combined water problems have a significant impact on the environment and socio-economic development of society.

This part underlines and discusses a combination of water shortage and water quality problems. In some cases, water is allocated to address both water problems. The degradation of water quality has a significant consequence, water becomes unfit for use and the water quantity availability is reduced. Often, the MCDM method is applied to tackle combined water problems of water quantity and quality. In this case, both multi-attribute decision-making and multi-objective decisions-making tools were used namely ELECTRE II, Fuzzy, and LP, respectively. Yang et al. [129] employed the ELECTRE II and AVF (Additive value function) methods to prioritize water management alternatives based on the DPSIR framework (Driving force-Pressure-State-Impact-Response). The research was applied to the Anyangcheon watershed in South Korea to examine the water allocation problem of the watershed, which has already suffered from potential streamflow depletion and possible water quality deterioration [130]. Their research improved and modified the set of criteria used earlier by Reference [131]. The criteria selected have mainly focused on satisfying the demands on water quality and quantity need. The result report shows that AVF is easy and convenient to be used. However, ELECTRE II is more effective and it shows the outranking priorities of the alternatives. This indicates that the ELECTRE method is an ideal tool for prioritizing alternatives with respect to water quality and quantity problems. However, they did not consider the impact of water price on the decision-making process and also used only limited water pollutant materials for determining the characteristics of the mining sites. Hence, in the future, these components ought to be underlined for optimal water management strategies. The other form of multi-attribute decision making used is modified fuzzy social choice (MFSC). This method was applied by Pourmand and Mahjouri [132]. The objective of the study was to find a socially optimal scenario for water allocation and reuse in Tehran, Iran. There has been a growing concern about the increase of water demand and pollution by wastewater from the agricultural and industrial sectors. To address the existing water allocation problems, they proposed scenarios for the water quantity and quality management by considering multi-stakeholders' conflicting utilities, negotiation power, degree of importance, and uncertainties. Eventually using the MFSC method, socially acceptable scenarios were prioritized to address water allocation problems of Tehran city. In their result analysis, the MFSC method has some advantages like its flexibility in defining preferences and incorporating imprecise input information using fuzzy membership functions. The method requires less mathematical calculations. However, they did not include uncertainties associated with water availability and reclaimed wastewater.

From the MODM class, LP was applied by Ke et al. [133] to optimize water allocation in Ordos city, China, by considering water quantity and water quality aspects of the Ordos river. The quality had been affected by mining industries. The LP method is used to address water allocation with reference to water quantity and to reclaim polluted water. They discussed that the dynamic linear optimization model can elaborate and simultaneously address problems related to water shortage and water quality.

In summary, mathematical programming (LP) was predominantly employed to address combined water problems. ELECTRE II and MFSC were preferably used to prioritize multi-attribute water management alternatives.

Water Shortage and Flood Problems

As discussed in the intergovernmental panel on climate change IPCC [134] assessment report, arid and semi-arid areas are particularly exposed to the impacts of climate change on water resource availability. This creates temporal and spatial variability in water resource distribution particularly in, e.g., Mediterranean Basin, western United States, and major parts of Africa, northeast Brazil, southern and eastern Australia. There is a discrepancy in water uses and users. Therefore, water resource management is crucial to satisfy the demand–supply relationship. Since the flow of a river is highly dependent on the seasonal climatic variation, it drives water managers to harvest water during the wet season to minimize water shortage during the dry season. One of the water resources management strategies is building water resources structures along a river basin such as dykes and reservoirs to store water [135]. However, it has been very challenging to optimally control reservoir water operations for water resource planners and managers. When the reservoirs get sufficient water supply in a wet period, then it is possible to control the water level to minimize flood risk to downstream areas. In normal periods of reservoir operation, all planned demands are met, the reservoir storage level is kept at or above the intended level. While during dry periods, when the reservoir storage level falls, the reservoir release is reduced to maintain a sufficient amount of water remaining in the reservoir for future water supply. This kind of situation seeks appropriate multi-criteria decision-making methods to optimally solve the existing conflicting trade-offs objectives, meeting ongoing water users′ demand, minimizing flood risks, and ensuring adequate reservoir storage when inflow is insufficient [136]. The MCDM methods are useful in situations where there is a decision-making that must meet multiple objectives in an integrated manner [135].

More often optimization is applied in reservoir water resource allocation to address a combined water shortage and flooding problem. Veintimilla-Reyes et al. [137] developed a generic linear programming model to optimize water allocation from a networked reservoir system to meet multiple spatially and temporally distributed water demands, reducing flood from maximum capacity and minimizing costs associated with unmet demand and flood events. The report shows that the LP model effectively optimizes the spatiotemporal allocation of water on a connected reservoir system. They suggested the model can be extended by considering other additional parameters like identifying new optimal locations for additional reservoirs.

5. Discussion

Water resources management is absolutely crucial for sustainable natural resource utilization and protection. Water resource management planning has to safeguard all the competing water demands and finds the best option to allocate water on an optimum basis to all demands and uses. The demand for water is rising due to many factors like global population growth and socio-economic development. These factors create pressure on the available limited water resources. Besides, global climate change affects water resources too. These factors make the use and allocation of water very complex and challenging. MCDM tools have been used to address the conflicting trade-offs in water resource distribution and management. Such methods are ideal and promising for optimizing water resources allocation in maximizing all benefits and reducing the risk associated with it. Researchers in different parts of the world have used MCDM methods to address water allocation problems. According to our review study, the trend analysis from 2000–2018 shows that the number of publications significantly increased particularly after 2014. One unanticipated finding was that there was no publication found between 2000 and 2006. The result of this study is similar to the result of de Brito and Evers [5], who reviewed the application of MCDM on flood risk management from 1995–2015. They indicated more publications were released after 2011 and there were equal to or less than one per year until 2004. Our results also reflect on those of Archibald and Marshall [6], who reviewed the application of mathematical programming on water resources management. They found that the number of publications increased from January 2010 to December 2017. This could be a reflection of the growing awareness of sustainable water resources management and the need for a more holistic approach towards complex water problems. This confirms that in the future, the number of publications will increase. The study of the distribution of publication based on the study region is useful to show where and how often the application of MCDM is used across the globe. In this study, at least 2 papers were reported from each continent and a total of 16 countries were listed. China has the first position; almost half of the publications originate from there. Similar review results were obtained by Archibald and Marshall [6] and Bhateria and Jain [101], which proved China is the top-ranked country. This may be due to the presence of multiple waterways and transboundary rivers that require the application of multi-objective decision-making tools. In contrast to the previous reviewers, Hajkowicz [7] reported that the USA and India were the prolific study regions. However, this study reviewed publications between 1973 and 2005, which is different from our study period.

An important topic emphasized and analyzed were criteria considered in the application of MCDM methods. Almost 50% of the papers considered economic and environmental factors, while the rest (around 40%) incorporated economic, environmental, and social aspects. There have been limited review studies that included the topic of these aspects in their paper. In summary, water resource management planning requires identifying and selecting appropriate criteria that consider the multifunctionality of water resource allocation. Hence, a good decision practice should be based on a critical analysis of the tradeoffs existing in the interaction of water resource management. Water is allocated to respond to different types of water problems like water shortage, water quality, water/environment ecosystem, and flood risk problems. Water shortage is the major problem reported, subsequently, water use management problem (regulations, policies), water quality problem, water ecosystem, and flood problem follow. In this review study, we found less attention was devoted to water allocation in response to flood problems, even if a flood is one of the worst natural hazards and affects a large portion of population and wealth. Some publications have also attempted to address simultaneously more than one water problem at the same time. Very often, water shortage and water quality problems happen at the same time. Normally, water quantity and quality are inherently related.

More publications are expected in the future to fill and cover this topic. In this study, we also reviewed publications that have used MCDM to address a combined water allocation problem of two antagonistic issues, i.e., water shortage and flooding problems at the same time. This kind of paper-primarily studies the reservoir water allocation problem that can sustain water supply and at the same time minimizes the overflow of water that could impact the downstream side. In the case of the geographical distribution of the publication in the context of water problem classifications, all the publications in all the listed water problems were concentrated in China. Some water problems were also reported in Iran and Taiwan. We can conclude that water allocation remains a fundamental problem in Asia. This might be associated with a combination of rapid population growth, environmental pollution from big industries, and climate change. The other point observed was that, even though water allocation is a critical problem in Africa and South America, there have been limited publications on those continents. Further studies should consider studying the status and condition of water resource allocation problems in those continents.

A number of multi-criteria decision-making methods were used to deal with different water allocation problems. For each specific water allocation issue, we found preferable decision methods that had been applied. For example, the heuristic methods Genetic algorithms (GA and NSGA II) and mathematical programming methods (LP forms like MILP, ILP) were the more frequently used for water shortage problems. NSGA II is the most commonly applied method for water use management problems. NSGA II and AHP methods are evenly used for water quality issues. GA and NSGA II were frequently implemented for water ecosystem/environment-related issues. In the case of flood risk problems, we found only a single publication that adapted the multi-objective best compromise decision model (MoBCDM). For a combined water problem (flood-water shortage and quality), there was no single outright decision technique employed. Nevertheless, relatively LP was slightly more applied compared to other methods.

Overall, this review research study reveals that NSGA II was the most commonly applied method, and GA and LP follow. In contrast to our conclusion, Archibald and Marshall [6] in their review study reported that stochastic dynamic programming and multistage stochastic programming were the frequently used methods. However, their review was concentrated on the broad aspect of water resource management and the review time-limited between 2010 and 2017. Another review study by Hajkowicz [7] indicated fuzzy, compromise programming, AHP, and ELECTRE were the most likely used methods. The same reason justifies that their review report focused on water resources planning and management and they used the time period between 1973 and 2005. Bhateria and Jain [101] discussed in their review that AHP and TOPSIS were the most popular methods. Their review was only targeted on flood risk management problems from 1995 to 2015. Our review report is different from the previous reviews in the sense that it specifically covering on recent publications and narrow context-based on publications dealing with water allocation problems.

In general, this study identified and demonstrated how decision-making methods are applied and employed to solve different water allocation problems. The results asserted and provided detailed information with regards to the application of different MCDM methods in the field of water allocation. In this paper, only a few studies used hybrid methods to address water problems. In the future, it is recommended to use a hybrid decision-making method and simultaneously attempt multiple objectives to solve complex water resources management and planning problems. In summary, the main intention of this review analysis was to give an overview and guidelines for researchers to select the appropriate decision tools to solve water allocation problems, based on repeatability and uncertainty, we suggested different possible decision methods for each type of water problems, besides the intention of the study was to show the trend and to provide updated information with respect to MCDM methods on water allocation problems. The paper contains intensive information for future researchers to use as a guideline. Furthermore, in the supplementary material (Table S1), the summary of each reviewed paper was presented in a structured manner for readers. This table is categorized into different water allocation problems and contains the description of problem gaps/motivations, objectives, criteria used, MCDM methods, and decision techniques employed.

6. Conclusions

This study carried out a systematic review of peer-reviewed publications on MCDM method applications with a focus on water allocation problems. The study used a literature web-based database source of WoS, Scopus, SD, and GS from January 2000 to December 2018. A total of 109 published articles were screened based on the title, keywords, and abstract. Forty-nine publication articles were selected and reviewed. Our findings show that MCDM application in the field of water allocation will continue to increase. More publications emerged particularly after 2014 as compared to the previous years. Sixteen countries as a study area applied MCDM methods with reference to water allocations. Nearly 65% and 12% of applications were conducted in Asia and Europe, respectively. Virtually, this review study is more a reflection of Asiatic and European water allocation problems. Note that this result is only based on the study origin and it did not consider experts′ origin.

MCDM tool has grown as part of operational research. It is a useful method for making decisions when there exist multiple conflicting criteria. It comprehensively targets to satisfy and meet multi-complex objectives and constraints. Notably, water allocations are interconnected with various dimensions like economical, environmental, and social factors. This study confirms that about 86% of papers considered more than one aspect of water allocation problems. Less than 10% of papers have considered only a single dimension. Regarding water problem context classifications, a range of different water problems were identified. Water shortage, water use management, and water quality were the most discussed water allocation problems. China is the top-ranked country where all water allocation problems were conducted. The study result report on the distribution of water shortage with respect to the study region is in line with the UN world water data report published in 2020 which classifies China, Burkina Faso, Iran, and Australia are mentioned in water scarcity areas [138].

Based on review findings, NSGA II is the most frequently used method followed by GA and linear programming forms. We can conclude MCDM techniques have been successfully implemented in various ranges of water allocation problems. However, many of the reviewed articles did not include sensitivity and uncertainties analysis in their MCDM study results. It is very relevant to identify sources of uncertainties and the way forward how to minimize them for further practical and operational applications in the field of water management. Moreover, many of the reviewed researches had not ascertained the issue of climate change in addressing water allocations.

In summary, this review paper rigorously covered and analyzed the state of the art of MCDM application in the field of water allocation problems. However, some limitations ought to be cautioned. Our review paper only focused on English peer-reviewed literature. Normally, important MCDM-based water allocation literature may be available in other languages and do not publish in high ranked journals. Even if it quite time-consuming to translate those literature and searching in databases, such types of literature are very crucial to grasp and collect relevant information on water allocation problems. Therefore, future review papers can consider other language-based scholarly articles and contain broad fields of water resources management problems. The results of this study report will provide substantial information and serve as a guide for future research on MCDM methods application to address water allocation problems.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4441/13/2/125/s1.

Author Contributions: Conceptualization, S.L.G., D.C., and J.V.O.; methodology, S.L.G., D.C., and J.V.O.; validation, S.L.G., D.C. and J.V.O.; formal analysis, S.L.G., D.C., and J.V.O.; investigation, S.L.G.; resources, D.C. and J.V.O.; data curation, S.L.G., D.C., and J.V.O.; writing—original draft preparation, S.L.G., D.C. and J.V.O.; writing—reviewing and editing, S.L.G., D.C., and J.V.O.; visualization, S.L.G.; supervision, D.C. and J.V.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: This research was performed as part of a PhD study. The study is supported by Global Mind′s scholarship. The views expressed in this review study are those of the authors and do not necessarily reflect the views or policies of Global Minds.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AHP	analytic hierarchy process
AVF	additive value function
CCM	compound cloud model
DE	differential evolution
DM	dynamic modeling
ELECTREE	elimination and choice expressing reality
e-NSGAII	epsilon dominance non-dominated sorted genetic algorithm-II
FAHP	fuzzy analytic hierarchy process
GA	genetic algorithm
GP	goal programming
GRASP	greedy randomized adaptive search procedure
IPCC	intergovernmental Panel on Climate Change
IQP	inexact quadratic programming
ITSP	inexact two-stage stochastic programming
LP	linear programming
MADM	multi-attribute decision-making
MAUT	multi-attribute utility theory
MCDM	multi-criteria decision-making
MFSC	modified fuzzy social choice
MFSP	multi-stage fuzzy stochastic programming
MIP	mixed-integer programming
MOABC	multi-objective artificial bee colony-based optimization approach
MoBCDM	multi-objective best compromise decision model
MODM	multi-objective decision-making
Model DSS	Innovative modeling approaches model (decision support system)
MOGM	multi-objective game-theory model
PROMETHEE	preference ranking organization method for enrichment evaluation
SA	simulating annealing
TOPSIS	technique for order of preference by similarity to ideal solution
WSM	weighted sum method

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