water

MDPI

Article

A Framework to Support the Selection of an Appropriate Water Allocation Planning and Decision Support Scheme

Johannes B. Nel [1,*], Paul T. Mativenga [1,2] and Annlizé L. Marnewick [1]

[1] Postgraduate School of Engineering Management, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg 2006, South Africa; amarnewick@uj.ac.za
[2] Department of Mechanical, Aerospace and Civil Engineering, School of Engineering, The University of Manchester, Manchester M13 9PL, UK; p.mativenga@manchester.ac.uk
* Correspondence: bultie1@gmail.com

Abstract: Water is becoming a scarce resource in many parts of the world, leading to increased competition amongst water users. Optimized water allocation is increasingly important to balance the growing demand for water and the limited supply of accessible clean water. The literature on water allocation schemes and decision support systems, developed for application in specific water management areas or watersheds, was critically reviewed. Although the literature is rich in studies on the application of a broad range of water allocation schemes, there is a lack of information available on the methodology and process of selecting the most applicable scheme that balances the local realities and requirements of stakeholders while considering the local context with regard to the economic, social and environmental impact of water usage. In this article, a framework is presented that water management practitioners can use to select applicable water allocation planning schemes and associated decision support systems based on the characteristics and requirements of the specific water management situation. The framework was used to analyse the water supply situation in South Africa (SA), taking broader factors into account. Based on this, a generic conceptualized water allocation planning and decision support framework for a typical SA water management area is proposed.

Keywords: water allocation scheme selection; water resource management; decision support system; water allocation planning

check for updates

Citation: Nel, J.B.; Mativenga, P.T.; Marnewick, A.L. A Framework to Support the Selection of an Appropriate Water Allocation Planning and Decision Support Scheme. *Water* **2022**, *14*, 1854. https://doi.org/10.3390/w14121854

Academic Editor: Ana Iglesias

Received: 9 May 2022
Accepted: 6 June 2022
Published: 9 June 2022

1. Introduction

Water allocation planning comprises two main functions: determining how much water is available within a certain region and then deciding how this water can be shared between the different competing water users within that region as well as with other local and international regions [1]. Traditionally, water demand–supply mismatches were addressed through the construction of new water infrastructure to address water availability in the context of water allocation [2,3]. With a limited supply of water in many areas of the world and the possible effects of climate change, fresh water is either already or becoming a scarce resource in many regions [4–6]. This reality, together with the substantial economic and environmental impacts of large-scale water projects, is limiting further water infrastructure construction in many countries [7–9].

Over the past few decades, several areas around the globe have also experienced a rapid growth in terms of the demand for water. This is driven mainly by growing populations, increased urbanization and an increased focus on economic growth [10–12]. The management of water demands has therefore grown in importance, and the second main function of water allocation planning, namely, optimized allocation, has become one of the most important and effective water management mechanisms in the balancing of water demands and available water supplies in modern times [2,9,13–15].

Several water allocation schemes, ranging from governmental-prescribed hierarchical priority schemes to strong market-orientated schemes [1,10,16,17], as well as a wide range of decision support systems [18–20] are described in the literature. Furthermore, the last few decades have been marked by a significant evolution in decision support systems as a result of developments in computer technology [18,21], and decision-making models used in watersheds have increased in terms of their sophistication and integrative capabilities [22,23]. It is not clear from the literature, however, how researchers and water management practitioners decide which specific water allocation decision-making scheme is the most applicable for use in a specific situation. Given the broad range of allocation schemes and decision support systems covered in the literature, together with the historical, social, economic, political, environmental, legal, stakeholder, technological and other realities of the specific region, water management practitioners are left with a complex task when it comes to deciding on which water allocation scheme or combination of schemes to utilize for optimal results in their region. When evaluating the literature, one also derives that, over the last two to three decades, the focus of water allocation decision support research shifted towards more integrated and computationally complex software. This presents further problems, as operational practitioners are frequently not keen to implement changes and decision-making tools are rarely used after research projects have ended [19,24,25]. Furthermore, upgrades and improvements to existing decision support systems have a better chance of being accepted [26,27], and stakeholder participation during the process is particularly important [28].

Several water allocation and decision support schemes described in the literature are reviewed in this article and a structured framework is proposed that can be applied by water management practitioners to analyse their specific water management situation and identify the water allocation planning and decision support schemes which are the most appropriate to be developed for their specific situation. The process is based on identifying the most important characteristics and priorities that influence water allocation and then selecting a water allocation planning scheme, with an associated decision support system, that can be developed to best support these priorities. The application of the framework is demonstrated by the proposal of an upgraded water allocation framework for South Africa (SA), which can be customized and further developed for its application in specific water management areas.

2. Materials and Methods

For well-researched topics, an integrative literature review provides an opportunity for consolidating knowledge and evolving understanding [29,30]. Since water management is a well-researched subject and a broad range of studies on numerous aspects of the subject are available, an integrative approach was used to review the literature and build a framework for selecting water allocation planning and associated decision support schemes.

The research approach diagrammatically presented in Figure 1 portrays the main steps of the integrative literature review, which was followed after implementing the guidelines proposed by Torraco [31]. The initial literature review focused on identifying generic water allocation schemes and their broad range of applications in different watersheds around the globe. To obtain a broad understanding of the drivers and schemes, a synthesis followed, after which the next stage of the literature review could be executed. This stage of the literature review focused on identifying situational characteristics, priorities and drivers as well as links to decision support systems which are important for the selection of water allocation schemes in the context of specific situations. Further synthesis led to a basic framework, highlighting the relationships between situation characteristics (drivers and priorities) and water allocation schemes. Lastly, the framework was applied to propose an upgraded water allocation planning scheme for a typical SA situation, which can be further developed in future research.

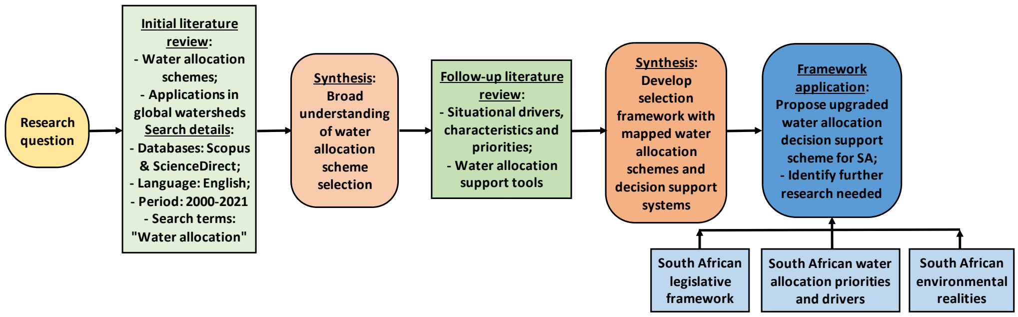

Figure 1. The research approach: an application of integrative literature review.

3. Literature Review

Starting with the first main function of water allocation planning, namely, the determination of available water, the modelling of the various individual components of the hydrological cycle dates back many years [22]. As computing power increased, and with parallel developments in such areas as remote sensing, satellites, radar applications and geographical information systems (GISs), hydrological process models also became more sophisticated [22], and well-integrated hydrological models could be developed and integrated in commercialized software programs [32,33]. With the modelling of water availability in South Africa being satisfactory [34], we do not address this aspect of water allocation, i.e., the determination of available water, in this article, but focus instead on the allocation of available water between users, and the decision-making schemes associated with this. When researching water allocation decision-making, there are three main factors to consider:

- The water allocation schemes described in the literature;
- The associated water allocation decision support systems;
- The specific water management situation's characteristics and the associated water allocation drivers and priorities.

3.1. Water Allocation Schemes

Traditionally, water allocation was based on social criteria to provide water for human consumption, sanitation and food production [16]. This was often achieved with the substantial involvement of governments, with the process being commonly referred to as public allocation. In most cases, not much attention was paid to economic efficiency. With population growth and increasing water scarcity, however, both the economic value and efficient use of water have become increasingly important over the past few decades. By treating water as an economic good, increased focus on decentralized management, a heightened reliance on pricing and the broad participation of all stakeholders became critical factors for successful water management [35]. Both the social and the economic value of water have to be recognized and taken into consideration [36]. Furthermore, the increased focus on environmental factors and climate change, socio-political realities and governments' developmental and strategic objectives, all result in an expanding range of objectives and uncertainties within the water sector [17,37]. Modern catchment planning therefore has to incorporate a wider range of issues and challenges combining the factors mentioned above [17]. Based on the required trade-offs between different social, economic, environmental and other objectives and needs, several authors have proposed similar categories of water allocation schemes [1,16,17].

After consolidating and integrating the work of these authors, the broadly defined categories of water allocation schemes listed below were identified:

1. Hierarchy or priority allocation is typically an administrative, public (governmental) method of allocating water in line with priorities that can be socially, politically, environmentally, strategically and/or economically orientated [1,38].

2. Strategic allocation is a public allocation method, whereby the government has very specific strategic objectives that it aims to achieve [1].
3. User-based allocation is aimed specifically at delegating the decision-making on a local level and involving stakeholders to such an extent that they regard the outcomes as fair and equitable [16].
4. Optimization-based allocation is aimed at achieving multiple objectives from the government and other stakeholders. It makes use of objective functions and goals that need to be optimized within a set of identified relationships and constraints [39–43].
5. Multiple-criteria-based allocation is based on evaluating and scoring different allocation scenarios against multiple criteria which may include social, economic and other factors. In general, this multi-criteria analysis is aimed at selecting an allocation scenario which is more equitable and acceptable to all stakeholders [44–47].
6. Price-driven allocation is based on the principle of the willingness of users to pay for additional water allocated to them. In this scheme, the water pricing has to be at a level which covers the marginal cost of supplying each additional unit of water [48].
7. Market-based allocation relies purely on market forces, with market instruments such as water markets, water trading or auctions determining the water allocation. In practice, this kind of allocation has to operate in parallel with another allocation scheme and under certain governmentally controlled rules and regulations [48].

3.2. Decision Support Systems

Water allocation schemes rely on optimized decision-making, and in most cases, decision support systems are needed to facilitate this decision-making. Several authors report that the application of decision support system technology in complex situations, such as in the context of water management, has developed significantly over the past number of decades [18,19]. Authors use different methods to categorize the broad range of decision support models and other tools available to decision-makers [20,49], but for this study, it made sense to link the classification of decision support tools to the categories used for water allocation schemes above:

1. Rule-based and hierarchy decision support is normally based on expert knowledge that is translated into rules and relationships to guide operation. It is also possible to use computer simulations as input to develop these rules and relationships [1]. Hierarchy or priority-based decision systems can be seen as a type of rule-based decision system with the rules based on legislation or strategic priorities [38,50,51].
2. Economic benefit models are based on maximizing the combined economic benefit for all water users and/or the community and are aimed at ensuring the economic sustainability of the allocation system [52–54]. Cost-benefit analysis is used to evaluate the benefits relative to costs in terms of water allocation and the system is aimed at maximizing the sum of the benefits. In order to address social and other non-economic aspects in water allocation, the economic benefit principle is frequently combined with multi-criteria systems [52,55,56].
3. The computable general equilibrium (CGE) method is also mainly economically orientated, but it combines economic theory with actual economic data to describe a whole economic unit and the interactions between the different parts (sectors, companies, households, government, markets) within it [57–59].
4. Game theory is based on actively involving stakeholders in the process of decision-making and conflict resolution in order to reach a well-balanced allocation situation [60–67]. Either cooperative or non-cooperative game theory approaches can be applied. The advantage of the cooperative methods lies in the way it motivates stakeholders to participate for the mutual benefit of all participants.
5. Multi-criteria analysis can be defined as a decision framework that scores and ranks the overall performance of different decision options against a range of multiple criteria. In this way, balanced allocation decisions are promoted [44,47,68,69].

6. Multi-objective analysis can effectively be classified as a multi-criteria analysis technique. Some authors, however, handle it as a separate technique, and specifically as an optimization method, that solves a set of multiple objectives which are to be satisfied simultaneously [39,41,70–74].
7. System dynamics (SD): Mirchi et al. [75] proposed the use of systems thinking in the form of SD to arrive at improved integrated solutions. Zomorodian et al. [23] executed a comprehensive review of the application of SD in water resource modelling. They found the technique to be appropriate for the solving of very complex multi-dimensional (watershed) problems but that it is also limited by a number of constraints.
8. Other systems, e.g., problem structuring methods [76,77], participatory modelling methodologies [78] and newsboy modelling techniques [79], do not present specific advantages and novelties in the context of this study, and are therefore not included in further analysis.

3.3. Water Allocation Drivers and Priorities

From the literature, it is clear that no one water allocation scheme can be regarded as superior in all circumstances, with the same being true for decision support systems [1,23]. Each water allocation scheme and decision support system has to be assessed on its ability to consider and balance economic, social, political, environmental, legal, stakeholder, technology and uncertainty factors and objectives relevant to the defined system boundary [23].

When evaluating water allocation and decision support systems, the situation needs to be analysed on the basis of the following list of characteristics, drivers and priorities:

1. Social and political dimensions: These refer to the social and equity orientation of the society impacted and the extent to which water is regarded as a social good [16,80–82].
2. Economic dimensions: These refer to the economic importance assigned to water, including cost recovery and associated pricing schemes [39,48,51,52,83].
3. Environmental dimensions: These include the ecological and environmental priorities and the relevant orientation of the society impacted [39,81,84,85]. The level of water conservation, demand management and water efficiency that will have to be implemented in the area are also included [1,53,86–88]. Furthermore, the interlinkage between the different resources (e.g., the food–water–energy nexus) and the resulting influence of water allocation on the other resources have to be taken into account [89–94].
4. Stakeholders: These would include the different categories of water users in a watershed relative to the water supply available [51,83,95–97], as well as the level of stakeholder participation expected [46,47,98,99]. The complexity of the catchment area and the range of challenges, objectives and issues that the allocation system needs to address also play an important role [39,47,68].
5. Legal framework: This refers to the water-related legal and institutional framework in the country [48,82,100,101].
6. Technical and knowledge base factors: These entail the availability of water management expertise amongst the decision-makers [47,49,51,68], the quantity, quality and uncertainty of the data available to support the decision-making process [102] as well as the availability of and need for computing power to support the requirements of the software [21,33,41,72,103].
7. Uncertainties and change: This element refers to the level of uncertainty and the sensitivity of the system to such uncertainties and changes [20,37]. Also included are the annual and seasonal variabilities that occur in the region and the flexibility required in the allocation system to provide for them [1,60,104].

4. Results and Framework Development

A qualitative evaluation of the water allocation schemes and decision support systems described in the literature relative to the relevant characteristics, drivers and priorities listed in the previous section, produces a number of clear patterns and relationships. The qualitative results for the water allocation schemes and decision support systems are summarized in matrix format in Tables 1 and 2, respectively. From the tables, it is clear that each of the different allocation schemes and decision support systems have areas of strengths and areas that are not well addressed. As an example, hierarchy/priority allocation schemes, typically backed by rule-based decision-making, tend to be socially oriented but with limited stakeholder participation, and a rather low number of priorities can be addressed using such schemes. These schemes do not need much computing power, but for them to be successful, high levels of water management expertise are required to set the priorities correctly. On the other hand, market-based allocation schemes are economically oriented, but are typically not socially and ecologically oriented. Stakeholder participation tends to be skewed towards economically active water users and the decision-making tends to focus on economic benefits. When water allocation necessitates that a wide range of priorities and criteria need to be taken into account and high levels of stakeholder participation is necessary, multi-criteria and optimization approaches are more applicable. In these cases, decision support systems such as game theory, multi-criteria analysis or system dynamics are more applicable. With such decision-making systems, rather high levels of water management expertise as well as reasonably high levels of computing power are necessary to achieve the desired results.

The analysis clearly shows that it is important to match the allocation scheme to the specific situation, with its unique characteristics, drivers and priorities. Depending on the situation, it might also be necessary to combine water allocation schemes to address a range of objectives that have to be met. While some of these characteristics or priorities are more or less independent, others are, to a certain degree, linked. In such cases, a water allocation scheme's orientation to one aspect might influence its orientation to another.

Following the qualitative analysis of allocation schemes and decision support systems, schematic presentations help to further improve understanding and demonstrate how different water allocation schemes support different evaluation areas. Figure 2 presents a qualitative evaluation of different allocation schemes relative to the philosophy of water being regarded as a social good as opposed to an economic good. It also presents the economic orientation of the allocation schemes relative to the ecological orientation. In this case, it is clear that the market-orientated allocation schemes will typically treat water as an economic good, whereas allocation with high governmental involvement can be more socially and ecologically orientated. Multi-criteria and optimization-orientated systems are in general more balanced, as multiple goals can be addressed at the same time.

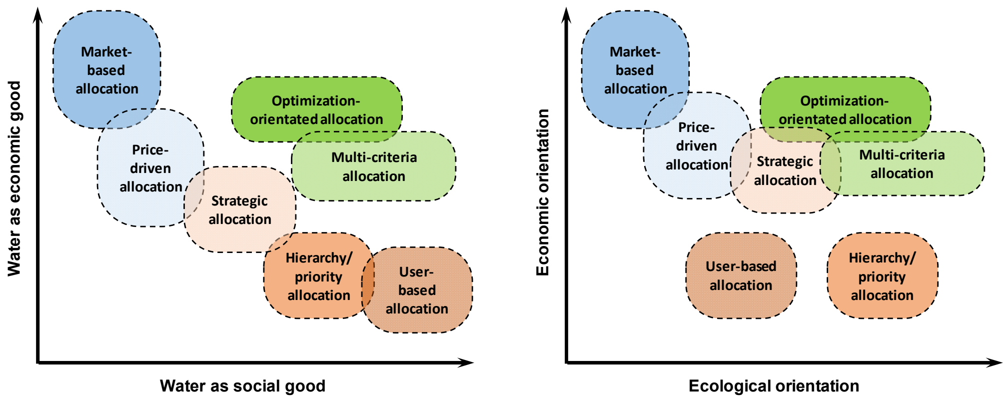

Figure 2. Social and ecological orientation of water allocation schemes relative to their economic orientation (Note: position and size of allocation scheme forms is purely schematic).

Table 1. (Simplified—refer to Appendix A Table A1 for details). Characteristics of different broad categories of water allocation schemes.

	Evaluation Area	Hierarchy/Priority Allocation	Strategic Allocation	User-Based Allocation	Optimization Approaches	Multi-Criteria Approaches	Price-Based Allocation	Market-Based Allocation
	Social/equity orientation	Medium/high	Medium	High	Medium	Medium	Low	Low
	Economic orientation	Medium/low	Medium/high	Low	Medium	Medium	Medium/high	High
Environmental dimensions	**Environmental orientation**	Medium/high	Medium	Medium	Medium	Medium	Medium	Low
	Promotion of water conservation and efficiency	Low/medium	Low	Medium	Medium/high	Medium/high	Medium	Low/medium
Stakeholders	**Stakeholder participation**	Low	Low	High	Medium/high	Medium/high	Low	Low/medium
	Complexity of catchment area that can be handled	Low/medium	Medium	Low/medium	Medium/high	Medium/high	Medium	Medium/high
	Range of challenges/ goals/issues handled	Limited range	Limited range	Reasonable range	Broad range	Broad range	Limited range	Limited range
	Categories of water users	Limited	Strategic only	Mostly socially driven	Multiple	Multiple	Multiple	Economically driven
	Categories of water supply	Any	Mostly strategic	Any	Complex combinations	Complex combinations	Source driven	Source driven
Legal framework	**Implementing legal framework**	Easy to enforce	Easy to enforce	Difficult to enforce	Work into objectives and constraints	Work into criteria, weighting and constraints	Complex to enforce	Difficult to enforce
	Level of water management and decision-making	Centralized decision-making; decentralized implementation	Decision-making and implementation centralized	Centralized policies/rules Decentralized implementation	Centralized or decentralized	Centralized or decentralized	Centralized guidelines; decentralized implementation	Centralized guidelines; decentralized implementation
Uncertainties/ change	**Overarching allocation vs. seasonal/annual variability**	Priorities determine all allocations	Strategic allocation will determine allocation	Allocation system will be used to handle both	Can handle both, two sets of objective functions	Can handle both, two sets of criteria and weightings	Seasonal and annual fluctuations through price premium	Market forces will determine allocation during variability
	Handling of uncertainties	Limited	Strategic users only	Work out solutions to limit overall impact	Work into objectives	Alternative scenarios as fall-back	Limited	Market forces

Table 2. (Simplified—refer to Appendix A Table A2 for details). Analysis of decision support systems and their application in different water allocation schemes.

Evaluation Areas	Rule-Based and Hierarchy Type	Economic Benefit Models	Computable General Equilibrium (CGE) Method	Game Theory	Multi-Criteria Analysis	Multi-Objective Analysis	System Dynamics
Water allocation schemes to which it can be applied	Hierarchy allocation system; partly strategic allocation	Market-based schemes; partly multi-criteria/ objective, price- and user-based schemes	Market-based schemes; partly multi-criteria/ objective, price- and user-based schemes	User-based schemes; Partly multi-criteria and multiple objective schemes	Multi-criteria allocation; partly user-based and optimization schemes	Multi-objective/ criteria schemes; partly user-based schemes	For complex systems and situations, multi-criteria/ objective schemes
Handling social/economic/ environmental balance	Through rules	Economic oriented; social and environmental through benefits and costs	Economic oriented; can evaluate environmental impact of on wider economy	Stakeholders from all areas must be presented	Incorporate balanced criteria	Incorporate balanced objectives	Through comprehensive modelling
Water conservation, improved water productivity	Through rule development	Linked to economic value of water	Linked to economic value of water	Introduce by facilitator or manager	Incorporate in selected criteria and weighting	Incorporate in objective and constraint sets	Incorporate in model setup
Stakeholder participation	Limited	Limited	Limited	Medium to high	Medium to high	Medium to high	High
Range of criteria incorporated	Limited range	Limited range	Limited range	Broad range	Broad range	Broad range	Broad, complex range
Reliance on expert knowledge	High to compile rules	Medium to high (economic)	Low to medium (economic expertise to set up model)	Low with expert facilitator	Expert knowledge to set up	Expert knowledge to set up	Expert knowledge to understand system
Reliance on computerized calculations	Low	Low to medium	High	Low	Medium	Medium to high	High
Type of computer use	Recording	Some calculations and recording	Comprehensive economic modelling	Recording	Recording and some calculations	Solving set of multiple objective functions	Solving the system dynamic setup
Overarching allocation vs. seasonal/annual variability	Rules for both	Mainly for overarching (long-term) allocation, other partly	Mainly for overarching (long-term) allocation, other partly	Aimed more at optimization of allocation	Through separate criteria/weighting sets	Through separate objective/constraint sets	Set up to cover all
Applicable for sensitivity analysis	Not suitable	To evaluate scenarios	Impacts on broader economy	Limited, scenarios can be inputs	Sensitivity analysis on weighting and performance	Good for sensitivity analysis	Limited use for sensitivity analysis

Of particular importance for countries implementing a modernized water framework through new water legislation, are the aspects presented in Figure 3. Market-orientated water allocation schemes will need more freedom through decentralized management, and, in this scenario, the implementation of legislation would be a challenge. Hierarchical allocation schemes are typically associated with centralized management, strict control and therefore easy legislative implementation. In general, market-orientated systems will be able to handle more complex catchment situations than hierarchical allocation systems. An economic orientation will also lead to better water efficiency than that achieved through legislative-based systems. Multi-criteria and optimization-orientated water allocation and decision systems are able to support reasonably well-balanced solutions. Depending on the specific situation, stakeholder participation might be critical to ensure that stakeholders accept the changes associated with the newly implemented water legislation. In modern times, stakeholder participation is also becoming increasingly important to ensure success in terms of water allocation, especially when a wide range of priorities and issues need to be addressed. Figure 4 shows the level of stakeholder participation relative to the range of objectives and criteria that can be covered by different allocation and decision support systems. The figure demonstrates that allocation decision systems that accommodate high levels of stakeholder participation can also accommodate a broad range of decision criteria.

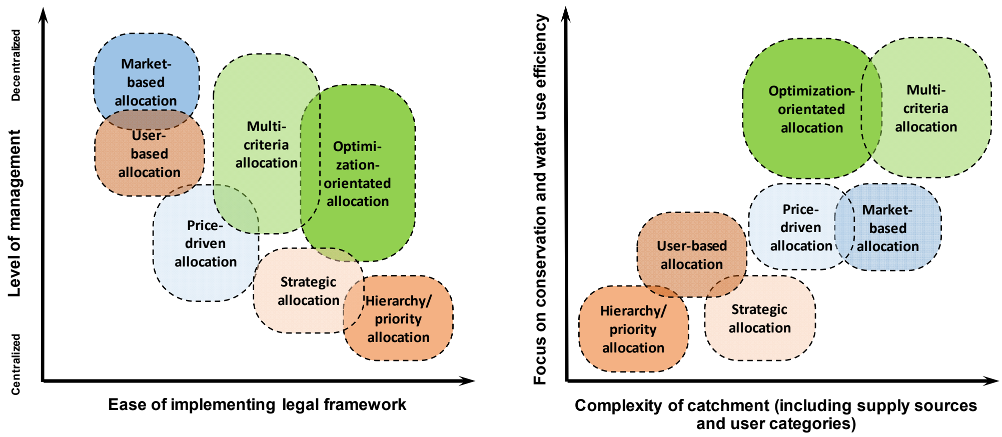

Figure 3. Implementing a country's legal framework and water conservation priorities in the case of different water allocation and decision-making schemes. (Note: Position and size of allocation scheme forms is purely schematic).

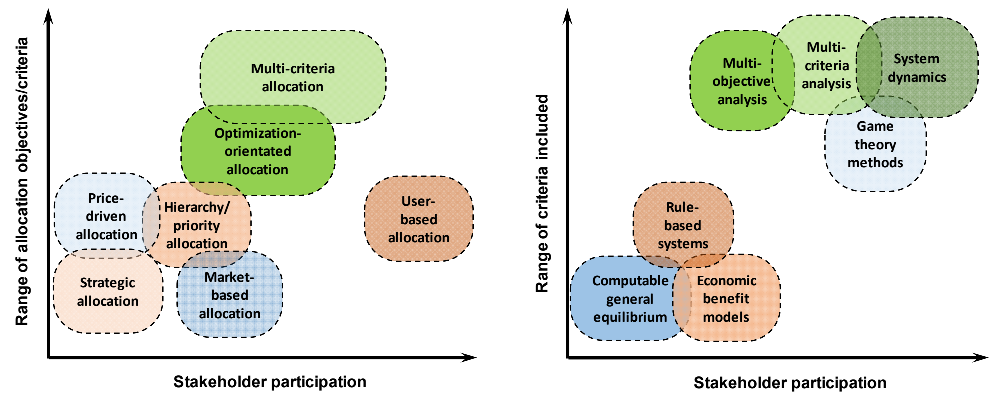

Figure 4. Level of stakeholder participation in water allocation and decision-making plotted against the range of allocation objectives and criteria that can be handled. (Note: Position and size of allocation scheme forms is purely schematic).

Figure 5 shows the reliance of the allocation decision systems on expert knowledge relative to computing capabilities. It shows that rule-based systems and system dynamics are highly dependent on expert knowledge, whereas the computable general equilibrium method is highly dependent on the available computing power and algorithms. Although game theory can be used without much need for either of these two factors, the other three water allocation decision systems are moderately dependent on both expert knowledge and computing power.

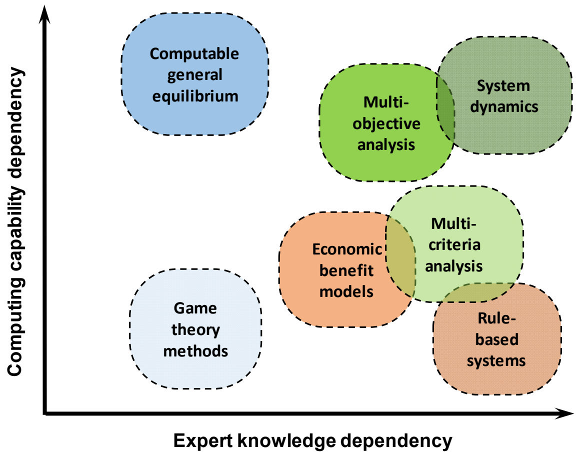

Figure 5. Decision support system dependence on expert knowledge and computing capabilities (Note: Position and size of decision support system forms is purely schematic).

Another very important aspect for many countries and associated watersheds is whether water allocation decision systems can deal with annual and seasonal variability [104]. This is one of the biggest challenges for water allocation management. Some allocation schemes that focus only on longer-term overarching allocation will have to be used in combination with other tools to address seasonal and annual variability [1]. A combination of decision support systems has in fact frequently been proposed by researchers, especially when applying multi-criteria, multi-objective analysis and system dynamics [23,55,70,71,73,105,106].

Framework Development Process

The results from the synthesis of the literature, taken together with the mapping matrices and diagrams, were used to identify those elements of the water allocation schemes and decision support systems that align best with the characteristics, drivers and priorities of a given water management situation. These elements can be used as the basis for developing a water allocation decision support system for the water management area under consideration. In this analysis, we took inspiration from the life cycle assessment methodology [90,107], and defined a framework for selecting and developing an appropriate water allocation decision system, which is diagrammatically presented in Figure 6. The framework steps in Figure 6 can be summarized as follows:

1. System boundaries: Define the boundaries of the allocation problem, covering the temporal and spatial dimensions of the water management area.
2. Evaluate the water management situation: Identify the external factors impacting the water management area, the water users and other stakeholders included within the system, as well as the cross-boundary water transfers required. Identify the available water sources within the system boundary, including possible inward transfers.
3. Develop and refine an inventory of priorities, drivers and assessment criteria: Evaluate the water management situation in the region or water management area, in order to identify the situation characteristics and water allocation priorities. Based on these, identify and decide on the water allocation drivers for this water management situation. Ensure that these priorities cover economic, social, environmental, legal, technological and change factors.

4. Evaluate alternative water allocation schemes based on refined priorities: Use the water allocation and decision support system matrices and figures developed earlier to identify those allocation schemes and decision support systems that are the most applicable or have elements that would be applicable to the situation. Also identify those schemes and support systems that are definitely not applicable to ensure that they are avoided. A combination of different water allocation schemes (i.e., hybrid schemes) also needs to be considered.
5. Interpret the allocation systems and align with priorities: The next step entails the development of the alpha version water allocation decision support system, by basing it on the elements identified. This step has to address both overarching (long-term) water allocation as well as annual and seasonal variations and uncertainties. It is important to note that most water management situations would require an approach that integrates elements from more than one water allocation scheme and/or decision support system (a hybrid system) in order to cover all the relevant priorities and allocation drivers.
6. Refinement and improvement: Finally, during operation, the water allocation results must be continuously evaluated according to the objectives, as this can inform and promote the future improvement of the allocation system.
7. Feedback loops: Although the flow of the framework developing process is mainly progressive in following the steps, as indicated in Figure 6, the feedback arrows indicate that information that becomes available in a certain step may have an influence on a previous step. The arrows labelled "A" indicate the refinement and improvement introduced during the definition of the water management situation, while the arrows labelled "B" indicate the flow of refinement and improvement data during the development of the water allocation scheme.

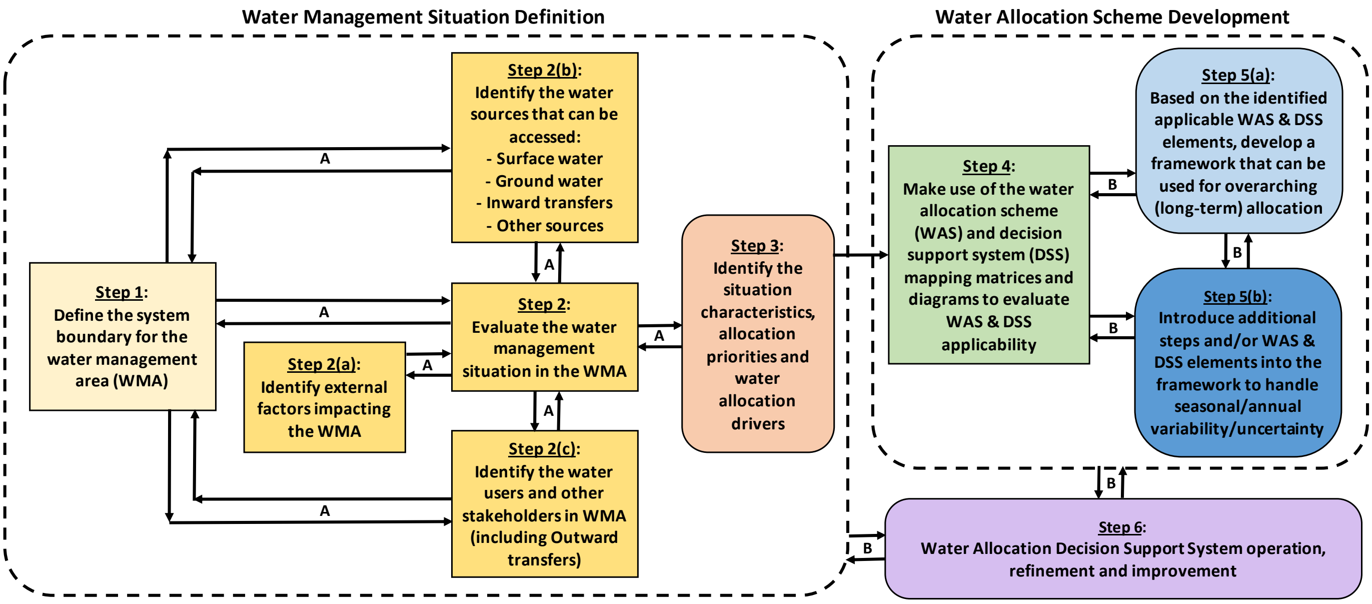

Figure 6. Framework for selecting and developing a water allocation planning scheme with an associated decision support system for a water management area. Note. The arrows labelled "A" indicate the refinement and improvement introduced during the definition of the water management situation, while the arrows labelled "B" indicate the flow of refinement and improvement data during the development of the water allocation scheme.

5. Implications for Framework Application in South African Water Management Areas

SA is regarded as the 30th most water-scarce country in the world [34]. However, for many years SA's water allocation system has been at the forefront of what has been available internationally [17,34,108]. The SA yield and planning models that were developed several decades ago for surface water [109] are still in use and are producing good results for determining the available water for allocation [34].

With regard to the allocation aspect of the water allocation process, the National Water Act [110], promulgated after SA's democratization, introduced new priorities with an increased focus on equity for all water users and ecological protection [111]. Some authors criticized SA water management for not implementing the principles laid out in the SA water Acts [112–114]. This, together with a significant evolution in decision support systems as a result of developments in computer technology [18,21], warrants a review of— and possible adjustments that could be made to the water allocation framework currently applied in SA. Upgrades to— and the improvement of existing decision systems have a better chance of success than implementing completely new decision support systems [26,27].

With regard to the first step in Figure 6, the National Water Act [110] promotes water management through catchment management agencies, defining the system boundaries for water allocation decision-making on a catchment area level. Moving to steps 2 and 3, the Act is prescriptive in terms of the priorities in water allocation, with the highest priority being water for the reserve, defined to include water for basic human and ecological needs. One of the most important principles within the current Act, is the principle of the equitable allocation of water to the members of the SA population. The Water Allocation Reform programme [115] sets out the priorities to achieve such equality. Given the criticism around implementation of the Act, one can reason that the most critical elements to be addressed by a water allocation scheme must be the enforcement of the legal framework, the implementation of the equity principles and achievement of the ecological objectives.

Although water for economic use has a relative low priority rating within the legal framework, several governmental strategic and planning documents highlight the importance of water as an economic enabler. The water allocation system for SA therefore has to balance social, environmental and economic priorities, and it is important to keep sufficient focus on economic development. In order to achieve the objectives of the Water Allocation Reform programme, the reallocation of water between users is unavoidable in most SA water management areas. To facilitate support for difficult reallocation decisions, the active participation of all stakeholders is a very important driver to consider. Given the level of water scarcity in South Africa, water conservation, water efficiency and water demand management is critical and therefore an important element when evaluating water allocation schemes [116–118]. Another important consideration is the allocation scheme's ability to address a broad range of challenges, goals and objectives.

Referring back to Table 1 and Figures 2–4, one can apply a simple scoring system to evaluate the different water allocation schemes with regard to the critical and important elements identified in a South African context. Table 3 presents the results and clearly indicates that the hierarchy/priority-based allocation scheme is ideal to address critical elements stemming mainly from the legislative aspects of the SA context and the priorities set out in the National Water Act and the Water Allocation Reform programme [115]. Furthermore, Table 3 highlights the fact that the other important driver elements that were identified are best addressed by the multiple criteria and optimization schemes. In a similar fashion, Table 2, together with Figures 2–5, can be used to score the available decision support systems in terms of supporting the hierarchy/priority-based and multiple criteria and optimization type schemes. In scoring these decision support tools, it is important to take into account the financial and human resource limitations of a developing country such as SA, as well as the ease of integrating new aspects introduced by the selected scheme into the existing practices within the water management area [26,27]. Table 4 present the scores and confirms that rule-based (hierarchy type) support system, applied together with a multi-criteria or multi-objective system would be the best combination to implement in the SA environment, with the further use of game theory being a possibility in selected water management areas.

Table 3. Scoring water allocation schemes (WAS) applied in SA water management areas.

	Evaluation Elements	Priority/Hierarchy	Strategically Focussed	User-Based	Optimized Objectives	Multi-Criteria	Price-Based	Market-Based
Critical implementation	Legal framework	4	2	1	2	2	1	1
	Equity	3	2	4	2	2	1	1
	Ecological objectives	4	2	2	3	3	2	1
	Total	**11**	**6**	**7**	**7**	**7**	**4**	**3**
Important elements to address	Economic development	2	3	2	3	3	3	4
	Stakeholder participation	2	1	4	3	3	1	2
	Multiple objectives	1	1	2	3	4	2	1
	Conservation/efficiency focus	2	2	2	4	4	2	2
	Total	**7**	**7**	**10**	**13**	**14**	**8**	**9**

Scoring system: Levels of alignment ranked as 1—weak; 2—fair; 3—good; 4—very good. The bold are Totals (sum of figures above it in table).

Table 4. Scoring decision support systems associated with water allocation schemes identified in Table 3.

	Evaluation Elements	Rule-Based	Economic Benefit	CGE Method	Game Theory	Multi-Criteria	Multi-Objective	System Dynamics
Support priority/hierarchy WA	Applicability level	4	1	1	2	2	2	2
	Supporting balance	2	1	1	2	3	3	3
	Ease of integration	4	1	1	2	2	1	1
	Total	**10**	**3**	**3**	**6**	**7**	**6**	**6**
Support multi-criteria/objectives WA	Applicability level	1	2	2	2	4	4	4
	Supporting balance	2	2	2	3	4	4	3
	Computer dependence	3	3	1	4	3	2	1
	Expert dependence	1	2	3	3	2	2	1
	Conservation/efficiency focus	2	2	2	2	4	4	3
	Ease of integration	3	3	2	3	3	3	2
	Total	**12**	**14**	**12**	**17**	**20**	**19**	**14**

Scoring system: Levels of alignment ranked as 1—weak; 2—fair; 3—good; 4—very good. The bold are Totals (sum of figures above it in table).

In summary, the hierarchy/priority-based allocation scheme is ideal for addressing the legislative aspects in a SA context, while SA's broad range of challenges, goals and objectives, together with the requirement to balance social, environmental and economic priorities with regard to water allocation, align well with the multiple criteria and optimization schemes and their associated decision support systems. In order to combine the strengths of the different allocation schemes, the application of a hybrid scheme made up of elements from the most appropriate schemes would be best in SA. Figure 7 presents a generic water allocation decision support framework for application in SA water management areas.

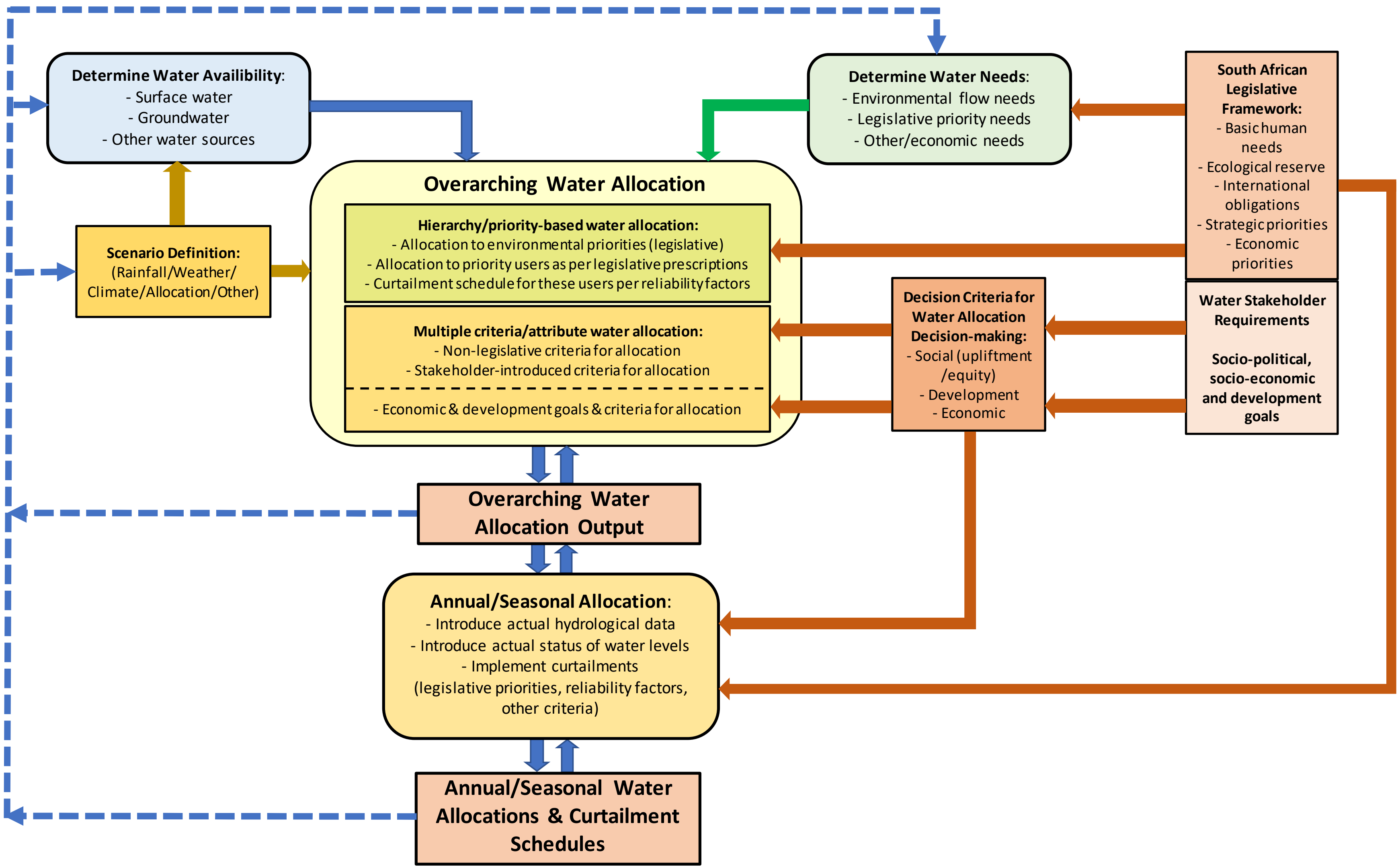

Figure 7. Generic water allocation and decision support framework for application in water management areas in SA.

Following the framework as presented in Figure 7, the process begins with the confirming of the system boundaries and the determining of the availability of water from surface water, groundwater and other sources, as well as the determining of the water needs for environmental, human, economic and other applications. The process of determining the groundwater and surface water available for allocation is based on historical weather and climate data, which, together with infrastructure information, serves as input to the relevant (existing) hydrological models that are used to predict the available water from each of these sources. Additional water can also be made available through inward transfers from other catchments and/or from other water sources such as reclaimed mine water, recycled water and desalination. When determining the water needs of users in the catchment, legal obligations as well as social and economic factors need to be considered. In line with legislation, the first requirement that must be quantified is environmental. The other priorities, for instance, the basic human right to water and international obligations, must also be quantified. Any other water users, e.g., industrial users, power industry users and other strategic and economically orientated users, must be identified, categorized and quantified.

The next step in the process is long-term (overarching) water allocation, which is achieved by taking pre-defined rainfall, weather and climate scenarios as well as guidelines from the SA legislative framework, water stakeholder requirements and socio-political, socio-economic and developmental goals into account. The legislative priorities are met by using the hierarchy/priority-based allocation scheme supported by a rule-based decision support system. The available water remaining after addressing the legislative priorities can then be allocated by implementing multiple criteria decision-making. The resulting overarching water allocation schedule/plan forms the input to an annual and seasonal allocation process. This annual and seasonal process uses actual hydrological data, the status of water levels in reservoirs and curtailment plans that were agreed with different users during the overarching water allocation process. Any planned curtailments have to take the legislative requirements into account. The output of this process will is an annual/seasonal water allocation and curtailment schedule. The complete process and system must be reviewed and improved periodically, taking end users' satisfaction and feedback loops into account. This can typically be achieved through periodic critical implementation review workshops and stakeholder satisfaction determination during stakeholder forums.

6. Discussion

In general, the water management areas in South Africa are well defined, but the formalization of the institutional structures is still ongoing, with a limited number of Catchment Management Agencies (CMAs) being institutionalized [119,120]. Water management in most, if not all, of the water management areas has been successful for many years, and the decision support tools, especially hydrological models, are well established and still produce acceptable results [34]. The current concerns with regard to water allocation are mainly linked to the reallocation of water to address legislative, socio-economic and equity factors [112–114] as well as balancing increasing demands associated with population growth and urbanization, and a limited supply of water [116,117]. The proposed framework is specifically aimed at addressing these concerns through the integration of additional water allocation principles into the existing South African water management systems, thereby improving the chance of successful implementation [26,27].

A study on the application of the developed framework to upgrade the water allocation system used in the Integrated Vaal River System (IVRS) is still ongoing and will be reported separately. The implications for the framework have been explored in this paper. This research was undertaken during the pandemic and social distancing limited our flexibility in terms of stake-holder engagement. Examples of elements that need urgent attention and which must be integrated into existing water allocation practices include a focus on water conservation, improving the efficiency of water use, curbing water loss and eradicating unlawful water use. Many of these aspects have also been identified by other authors [116–118], but are not effectively being worked into water allocation decision-making at the present moment. Furthermore, the available water within the case study area (IVRS system) is currently fully allocated, making it difficult to address inequalities that have resulted from historic allocation principles. The successful implementation of demand management, water loss prevention and unlawful use eradication principles will help to make water available to address water reformation objectives.

The IVRS system is very established and has been thoroughly analysed over the past three decades, with a rich body of information available to researchers and water practitioners. Many lessons have been learned [118,121], and the proposed framework aims to effectively address some of the critical elements that are still outstanding through the integration of these elements into the water allocation process. The application of the framework indicates that the principles of a rule-based system, together with multi-criteria decision support, align well with the water management practises applied in the IVRS, and the main focus will have to be on the formal integration of critical elements that warrant attention.

7. Conclusions

Water scarcity is a problem for many countries, especially developing countries, and numerous research studies on water allocation and decision-making have been published over the past two decades. In this study, a large number of these documents were reviewed, and it was found that many countries are moving away from traditional water management practices that are focused on infrastructure development. Modern water planning and allocation focus on a much wider range of environmental, social and economic issues and challenges, require the participation of a wide range of decision-makers in the allocation process, and must conform to legal frameworks.

An integrative literature review was used to develop a generic framework which water management practitioners can use to make first-order selections of appropriate water allocation schemes and associated decision support systems for their specific water management requirements. These inputs can then be used as a basis to develop a relevant conceptualized water allocation decision system for a water management area. The developed framework was applied to the SA water arena, and a generic water allocation decision scheme for application in SA water management areas was developed. This SA scheme implements hierarchy/priority and multiple criteria water allocation schemes and their associated decision-making techniques.

Author Contributions: Conceptualization, J.B.N. and A.L.M.; methodology, J.B.N., P.T.M. and A.L.M.; analysis, J.B.N.; writing—original draft preparation, J.B.N.; writing—review and editing, P.T.M. and A.L.M.; supervision, P.T.M. and A.L.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work is based on research supported in part by the National Research Foundation of South Africa (NRF) under the Masters and Doctoral Scholarship programme.

Data Availability Statement: Not applicable.

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

Appendix A. Detailed Tables Presenting the Characteristics of Water Allocation Schemes and Associated Decision Support Systems

Table A1. Characteristics of different broad categories of water allocation schemes.

	Evaluation Area	Hierarchy/Priority Allocation	Strategic Allocation	User-Based Allocation	Optimization Approaches	Multi-Criteria Approaches	Price-Based Allocation	Market-Based Allocation
	Social/equity orientation	Depending on priorities, can be medium to high	Depending on priorities, probably medium	High—more socially-orientated	Medium—balanced	Medium—balanced	Relatively low	Low
	Economic orientation	Depending on priorities, probably medium-low	Depending on priorities, probably medium-high	Relatively low	Medium—balanced	Medium—balanced	Relatively high	High
Environmental dimensions	**Environmental/ ecological orientation**	Depending on priorities, can be high	Depending on priorities, probably medium	Depending on user understanding, probably medium	Medium—balanced	Medium—balanced	Medium, can be worked into pricing	Low
	Promotion of water conservation, demand management and improved water productivity	Low/medium—can be included as not strongly promoting these objectives	Low—can be included as not aimed at promoting these objectives	Medium—can be included as user group may regard these objectives as important	Medium/high—can be included as part of objective functions	Medium/high—can be included, as can be included as part of criteria to promote positive behaviour	Medium—can be included as address through pricing as users would want to save on water costs	Will promote higher water productivity but not necessarily conservation or demand management
Stakeholders	**Stakeholder participation**	Relatively small group and low participation	Relatively small group and low participation	Good participation of relevant stakeholders	Can be high	Can be high	Relatively low	Relatively small group, high participation
	Complexity of catchment area that can be handled	Low to medium	Medium	Low to medium	Medium to high	Medium to high	Medium	Medium to high
	Range of challenges/ goals/issues handled	Allocation in line with priorities, limited other issues/challenges	Allocation in line with priorities, limited other issues/challenges	Reasonable number of issues/challenges can be resolved	Challenges/issues built into objectives; solution becomes complex	Broad range of challenges/issues can be built into criteria and weighting; expert inputs necessary	Only challenges/issues that can be linked to price can be addressed effectively	Only challenges/issues that can be linked to market forces can be addressed effectively
	Categories of water users	Limited by priority list	Strategic user focus	Mainly social types	Multiple	Multiple	Multiple	Mainly economic driven
	Categories of water supply	Applied to any water supply category	Linked to specific strategic priorities	Can include what is locally available	Can handle complex combinations	Can handle complex combinations	Pricing will differ from source to source (complex)	Applied to relevant supply source considered

Table A1. *Cont.*

	Evaluation Area	Hierarchy/Priority Allocation	Strategic Allocation	User-Based Allocation	Optimization Approaches	Multi-Criteria Approaches	Price-Based Allocation	Market-Based Allocation
Legal framework	**Implementing legal framework**	Implemented through priority levels by public administrators	Implemented through strategic priorities by public administrators	Users will have to work within legal framework; could be difficult to enforce	Legal framework worked into objectives and constraints	Legal framework worked into criteria, weighting and constraints	Implemented through pricing in line with legal framework by public administrators	Market will have to operate within legal framework; could be difficult to enforce
	Level of water management and decision-making	In general, decision-making centralized but implementation can be at lower (local) level	Decision-making as well as implementation tend to be centralized	Decentralized implementation with some centralized guid-ance/policies/rules possible	Can work at centralized as well as decentralized levels of management	Can work at centralized as well as decentralized levels of management	Guidelines and setting of prices probably from a centralized level with decentralized implementation	Mainly at a decentralized level where users and user organizations make decisions on water trading
Uncertainties/change	**Overarching allocation vs. seasonal and annual variability**	Priorities determine all allocations—in times of lower water availability, only higher priorities will be serviced	Strategic allocation will determine overarching allocation; handling of variability will depend on negotiated user ability to cope with variations	Allocation system will be used to handle both long- and short-term allocation; social needs will receive priority during times of low availability	Can handle both, may be necessary to handle with two different sets of objective functions and constraints	Can handle both, may be necessary to handle with two different sets of criteria and weightings	Normally used together with another allocation scheme to ensure cost recovery; seasonal and annual fluctuations through price premium	Limited application in overarching water allocation—rather used for reallocation and market forces will determine allocation levels during variability
	Handling of uncertainties	Not equipped to deal with much uncertainty	Strategic users covered, others not	Work out solutions to limit overall impact	Somewhat complex to work into objectives	Work out alternative scenarios as fall-back	Pricing levels based on certainty with limited variation	Covered in terms of market forces

Table A2. Analysis of decision support systems and their application in different water allocation schemes.

Evaluation Areas	Rule-Based and Hierarchy Type	Economic Benefit Models	Computable General Equilibrium (CGE) Method	Game Theory	Multi-Criteria Analysis	Multi-Objective Analysis	System Dynamics
Water allocation schemes to which it can be applied	Applicable mainly to hierarchy allocation system and to a degree to strategic allocation	Can provide inputs to market-based schemes; frequently part of broader multi-criteria and multi-objective schemes; can add value to price- and user-based schemes	Can provide inputs to strategic schemes; can form part of broader multi-criteria and multi-objective schemes; can add value to price- and user-based schemes	Specifically linked to user-based schemes, but can be used in combination with multi-criteria and multiple objectives in other schemes	Specifically linked to multi-criteria allocation; can provide valuable inputs on user-based and optimization schemes	Specifically linked to optimization and multi-criteria allocation schemes; can provide valuable inputs on user-based schemes	Specifically applicable in complex systems and situations, i.e., linked mainly to optimization and multi-criteria allocation schemes

Table A2. *Cont.*

Evaluation Areas	Rule-Based and Hierarchy Type	Economic Benefit Models	Computable General Equilibrium (CGE) Method	Game Theory	Multi-Criteria Analysis	Multi-Objective Analysis	System Dynamics
Handling social/economic/ environmental balance	Rules will address the balance; normally more socially and environmentally orientated	Mainly economically oriented but can include social and environmental aspects in terms of benefits and costs specifically	Mainly economically oriented but can be used to evaluate the impact of environmental water allocation on the wider economy	To ensure balance, stakeholders from all areas must be present—especially those from environmental areas	A well-balanced solution can be achieved by incorporating balanced criteria	A well-balanced solution can be achieved by incorporating balanced objectives	A well-balanced solution can be achieved by ensuring that the system is comprehensively modelled
Water conservation, demand management and improved water productivity	Could be included in rule development, but not for specific application	Can promote these initiatives as they are linked to economic value of water	Can promote these initiatives as they are linked to economic value of water	These objectives are not specifically addressed, but can be introduced by facilitator or manager	Can specifically be incorporated in selected criteria and weighting	Can specifically be incorporated in objective and constraint sets	Can specifically be incorporated in model setup
Level of stakeholder participation	Very limited except if forms part of expert knowledge base	Relatively low level of stakeholder participation—for determining benefiting groups and levels only	Limited stakeholder participation; can be used to help stimulate dialogue between decision-makers from governmental and economic backgrounds	Works best when all stakeholders are actively working together to reach a solution	Stakeholder participation can vary—good to involve in criteria identification	Stakeholder participation can vary—good to involve them in objective and constraint identification	Stakeholder participation is an important aspect, and it is important to draw from broad knowledge base
Range of criteria incorporated	Limited range of criteria to avoid complexity	Only benefits and costs, both economic, broaden by combination with multi-criteria or multi-objectives	Orientated towards broader economic aspects only	Covers a broad range of criteria through the priorities of participating stakeholders	Aims specifically to cover a broad range of criteria to address complex allocation problems	Aims specifically to cover a broad range of criteria through multiple objectives and constraints	Specifically aimed at covering a broad, complex range of criteria, objectives and constraints
Reliance on expert knowledge	Relies heavily on expert knowledge; rules also strategic and legislative based	Rely to a degree on expert knowledge, specifically from an economic background	Combine economic theory with actual economic data—economic expertise necessary in setting up the model	Aimed at reaching a negotiated compromise—expert facilitator can help	Expert knowledge contributes to criteria selection and weighting as well as performance scoring	Expert knowledge required in identifying specific objective functions and constraints	Expert knowledge required for accurate and comprehensive understanding of the system
Reliance on computerized calculations	Limited computer calculations except if simulations are needed	Limited computer calculation except if complex economic model is used	Relies heavily on computer modelling of the economic units and the other interacting sectors and parts of the economy	Not much reliance on any computerized work—simulations of scenarios can be valuable inputs	Computerized calculations not critical, but used in some multi-criteria analysis techniques	Similar to multi-criteria analysis, but specifically computer-based	Substantial computational capacity needed, but running time shorter than some simulation methods

Table A2. *Cont.*

Evaluation Areas	Rule-Based and Hierarchy Type	Economic Benefit Models	Computable General Equilibrium (CGE) Method	Game Theory	Multi-Criteria Analysis	Multi-Objective Analysis	System Dynamics
Type of computer use	Recording and possibly simulation	Some calculations and recording	Needed to run the comprehensive economic model	Recording and possibly some simulated inputs	Recording and some calculations	Used in solving set of multiple objective functions	Used in solving the set of relationships, feedback loops and flow diagrams
Overarching allocation vs. seasonal and annual variability	Can be applied in both, frequently used together with others to address specifically seasonal variations via rules	In general, applied more in overarching (long-term) allocation, but can add value in seasonal and annual allocation	In general, applied more in overarching (long-term) allocation, but can add value in analysis of seasonal and annual allocation	Aimed more at optimization of allocation, i.e., use another decision support tool such as economic analysis for initial allocation and game theory to optimize	Can be set up to cover both overarching seasonal/annual allocations—best used with separate criteria/weighting sets	Can be set up to cover both overarching seasonal/annual allocations—best used with separate objective sets	Can be set up to cover overarching, seasonal and annual allocations
Applicable for sensitivity analysis	Not suitable, adjust rules for scenarios	Limited application to evaluate scenarios	Good tool to use in evaluating impacts on broader economy	Not specifically suited for sensitivity analysis; scenarios can be inputs	Sensitivity analysis on weighting and performance scoring important	Good for sensitivity analysis	Can be used for sensitivity analysis but not a specific strength

References

1. Speed, R.; Yuanyuan, L.; Le Quesne, T.; Pegram, G.; Zhiwei, Z. *Basin Water Allocation Planning: Principles, Procedures and Approaches for Basin Allocation Planning*; 2013; 143p. Available online: https://think-asia.org/handle/11540/82. (accessed on 16 June 2020).
2. Tian, J.; Guo, S.; Liu, D.; Pan, Z.; Hong, X. A fair approach for multi-objective water resources allocation. *Water Resour. Manag.* **2019**, *33*, 3633–3653. [CrossRef]
3. Khare, D.; Jat, M.K.; Sunder, J.D. Assessment of water resources allocation options: Conjunctive use planning in a link canal command. *Resour. Conserv. Recycl.* **2007**, *51*, 487–506. [CrossRef]
4. Hipel, K.W.; Fang, L.; Wang, L. Fair water resources allocation with application to the South Saskatchewan river basin. *Can. Water Resour. J.* **2013**, *38*, 47–60. [CrossRef]
5. Mendelsohn, R. Adaptation, Climate Change, Agriculture, and Water. *Choices—A Publ. Agric. Appl. Econ. Assoc.* **2016**, *31*, 1–7. Available online: https://www.jstor.org/stable/choices.31.3.03?seq=1 (accessed on 25 June 2020).
6. Yin, J.; Gentine, P.; Zhou, S.; Sullivan, S.C.; Wang, R.; Zhang, Y.; Guo, S. Large increase in global storm runoff extremes driven by climate and anthropogenic changes. *Nat. Commun.* **2018**, *9*, 4389. [CrossRef]
7. Gleick, P.H. Water in crisis: Paths to sustainable water use. *Ecol. Appl.* **1998**, *8*, 571–579. [CrossRef]
8. Fletcher, S.M.; Miotti, M.; Swaminathan, J.; Klemun, M.M.; Strzepek, K.; Siddiqi, A. Water supply infrastructure planning: Decision-making framework to classify multiple uncertainties and evaluate flexible design. *J. Water Resour. Plan. Manag.* **2017**, *143*, 04017061. [CrossRef]
9. Wang, S.; Huang, G.H. Identifying optimal water resources allocation strategies through an interactive multi-stage stochastic fuzzy programming approach. *Water Resour. Manag.* **2012**, *26*, 2015–2038. [CrossRef]
10. Meinzen-Dick, R.; Ringler, C. Water Reallocation: Drivers, Challenges, Threats, and Solutions for the Poor. *J. Hum. Dev.* **2008**, *9*, 47–64. [CrossRef]
11. Gleick, P.H. Transitions to freshwater sustainability. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 8863–8871. [CrossRef]
12. Gong, X.; Zhang, H.; Ren, C.; Sun, D.; Yang, J. Optimization allocation of irrigation water resources based on crop water requirement under considering effective precipitation and uncertainty. *Agric. Water Manag.* **2020**, *239*, 106264. [CrossRef]
13. Bijl, D.L.; Biemans, H.; Bogaart, P.W.; Dekker, S.C.; Doelman, J.C.; Stehfest, E.; van Vuuren, D.P. A global analysis of future water deficit based on different allocation mechanisms. *Water Resour. Res.* **2018**, *54*, 5803–5824. [CrossRef]
14. Liu, D.; Guo, S.; Shao, Q.; Liu, P.; Xiong, L.; Wang, L.; Hong, X.; Xu, Y.; Wang, Z. Assessing the effects of adaptation measures on optimal water resources allocation under varied water availability conditions. *J. Hydrol.* **2018**, *556*, 759–774. [CrossRef]
15. Hellegers, P.; Leflaive, X. Water allocation reform: What makes it so difficult? *Water Int.* **2015**, *40*, 273–285. [CrossRef]
16. Dinar, A.; Rosegrant, M.W.; Meinzen-Dick, R. *Water Allocation Mechanisms: Principles and Examples*; World Bank Publications: Washington, DC, USA, 1997. [CrossRef]
17. Pegram, G.; Yuanyuan, L.; Le Quesne, T.; Speed, R.; Jianqiang, L.; Fuxin, S. River Basin Planning: Principles, Procedures and Approaches for Strategic Basin Planning. 2013. Available online: https://www.adb.org/publications/river-basin-planning-principles (accessed on 16 June 2020).
18. Shim, J.P.; Warkentin, M.; Courtney, J.F.; Power, D.J.; Sharda, R.; Carlsson, C. Past, present, and future of decision support technology. *Decis. Support Syst.* **2002**, *33*, 111–126. [CrossRef]
19. Giupponi, C.; Sgobbi, A. Decision support systems for water resources management in developing countries: Learning from experiences in Africa. *Water* **2013**, *5*, 798–818. [CrossRef]
20. Mabaya, G. *Decision Support Systems for Water Environment Management in Rural Areas under Hydrological and Socio-Economic Uncertainties*; Kyoto University: Kyoto, Japan, 2016.
21. Westphal, K.S.; Vogel, R.M.; Kirshen, P.; Chapra, S.C. Decision Support System for Adaptive Water Supply Management. *J. water Resour. Plan. Manag.* **2003**, *129*, 165–177. [CrossRef]
22. Mirchi, A.; Watkins, D.; Madani, K. Modeling for watershed planning, management, and decision making. In *Watersheds: Management, Restoration and Environmental Impact*; Vaughn, J.C., Ed.; Nova Science Publishers, Inc.: Hauppauge, NY, USA, 2010; pp. 221–244. ISBN 9781616686673.
23. Zomorodian, M.; Lai, S.H.; Homayounfar, M.; Ibrahim, S.; Fatemi, S.E.; El-Shafie, A. The state-of-the-art system dynamics application in integrated water resources modeling. *J. Environ. Manage.* **2018**, *227*, 294–304. [CrossRef]
24. Balsam, G. Decision Support Systems for Water Management: Investigating Stakeholder Perceptions of System Use. 2016. Available online: http://libproxy.lib.unc.edu/ (accessed on 1 July 2020).
25. Junier, S.; Mostert, E. A decision support system for the implementation of the Water Framework Directive in the Netherlands: Process, validity and useful information. *Environ. Sci. Policy* **2014**, *40*, 49–56. [CrossRef]
26. Borowski, I.; Hare, M. Exploring the gap between water managers and researchers: Difficulties of model-based tools to support practical water management. *Water Resour. Manag.* **2007**, *21*, 1049–1074. [CrossRef]
27. Van Delden, H.; Seppelt, R.; White, R.; Jakeman, A.J. A methodology for the design and development of integrated models for policy support. *Environ. Model. Softw.* **2011**, *26*, 266–279. [CrossRef]
28. Serrat-Capdevila, A.; Valdes, J.B.; Gupta, H.V. Decision Support Systems in Water Resources Planning and Management: Stakeholder participation and the sustainable path to science-based decision making. In *Efficient Decision Support Systems—Practice and Challenges From Current to Future*; Jao, C., Ed.; IntechOpen: London, UK, 2011.
29. Snyder, H. Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [CrossRef]

30. Webster, J.; Watson, R.T. Analyzing the past to prepare for the future: Writing a literature review. *MIS Q.* **2002**, *26*, xiii–xxiii. [CrossRef]
31. Torraco, R.J. Writing integrative literature reviews: Guidelines and examples. *Hum. Resour. Dev. Rev.* **2005**, *4*, 356–367. [CrossRef]
32. Devi, G.K.; Ganasri, B.P.; Dwarakish, G.S. A Review on Hydrological Models. *Aquat. Procedia* **2015**, *4*, 1001–1007. [CrossRef]
33. Golmohammadi, G.; Prasher, S.; Madani, A.; Rudra, R. Evaluating Three Hydrological Distributed Watershed Models: MIKE-SHE, APEX, SWAT. *Hydrology* **2014**, *1*, 20–39. [CrossRef]
34. Seago, C. A Comparison of the South African Approach to Water Resources Management and Planning with four International Countries (Report to the Water Research Commission). 2016. Available online: http://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/KV%20341-15.pdf (accessed on 7 October 2020).
35. World Bank. *Water Resources Management: A World Bank Policy Paper*; World Bank: Washington, DC, USA, 1993.
36. Jiang, M. *Towards Tradable Water Rights: Water Law and Policy Reform in China*; Dinar, A., Ed.; Springer Nature, Springer International Publishing: Cham, Switzerland, 2018; ISBN 9783319670850.
37. Pyke, C.R.; Bierwagen, B.G.; Furlow, J.; Gamble, J.; Johnson, T.; Julius, S.; West, J. A decision inventory approach for improving decision support for climate change impact assessment and adaptation. *Environ. Sci. Policy* **2007**, *10*, 610–621. [CrossRef]
38. Tyagi, A.; Shortle, J.S. Modeling Endogenous Change in Water Allocation Mechanisms: A Non-Cooperative Bargaining Approach. In Proceedings of the 2016 Annual Meeting—Agricultural and Applied Economics Association (AAEA) Conferences, Boston, MA, USA, 31 July–2 August 2016; p. 28. Available online: http://purl.umn.edu/235571 (accessed on 17 August 2020).
39. Roozbahani, R.; Schreider, S.; Abbasi, B. Multi-objective decision making for basin water allocation. In Proceedings of the 20th International Congress on Modelling and Simulation, Adelaide, Australia, 1–6 December 2013; pp. 2973–2979. [CrossRef]
40. Tu, Y.; Zhou, X.; Gang, J.; Liechty, M.; Xu, J.; Lev, B. Administrative and market-based allocation mechanism for regional water resources planning. *Resour. Conserv. Recycl.* **2015**, *95*, 156–173. [CrossRef]
41. Kiani-Moghaddam, M.; Shivaie, M.; Weinsier, P.D. Introduction to Multi-objective Optimization and Decision-Making Analysis. In *Modern Music-Inspired Optimization Algorithms for Electric Power Systems*; Springer: Cham, Switzerland, 2019; pp. 21–45. Available online: http://link.springer.com/10.1007/978-3-030-12044-3 (accessed on 21 August 2020).
42. Yan, D.; Ludwig, F.; Huang, H.Q.; Werners, S.E. Many-objective robust decision making for water allocation under climate change. *Sci. Total Environ.* **2017**, *607–608*, 294–303. [CrossRef]
43. Zhao, S.; Liu, W.; Zhu, M.; Ma, Y.; Li, Z. A priority-based multi-objective framework for water resources diversion and allocation in the middle route of the South-to-North Water Diversion Project. *Socioecon. Plann. Sci.* **2021**, *78*, 101085. [CrossRef]
44. Hajkowicz, S.; Higgins, A. A comparison of multiple criteria analysis techniques for water resource management. *Eur. J. Oper. Res.* **2008**, *184*, 255–265. [CrossRef]
45. Elleuch, M.A.; Anane, M.; Euchi, J.; Frikha, A. Hybrid fuzzy multi-criteria decision making to solve the irrigation water allocation problem in the Tunisian case. *Agric. Syst.* **2019**, *176*, 102644. [CrossRef]
46. Kapetas, L.; Kazakis, N.; Voudouris, K.; McNicholl, D. Water allocation and governance in multi-stakeholder environments: Insight from Axios Delta, Greece. *Sci. Total Environ.* **2019**, *695*, 133831. [CrossRef]
47. Hajkowicz, S.; Collins, K. A review of multiple criteria analysis for water resource planning and management. *Water Resour. Manag.* **2007**, *21*, 1553–1566. [CrossRef]
48. Rey, D.; Pérez-Blanco, C.D.; Escriva-Bou, A.; Girard, C.; Veldkamp, T.I.E. Role of economic instruments in water allocation reform: Lessons from Europe. *Int. J. Water Resour. Dev.* **2019**, *35*, 206–239. [CrossRef]
49. Power, D.J. *Decision Support Systems: Concepts and Resources for Managers*; 2002; 251p, Available online: https://scholarworks.uni.edu/facbook/67 (accessed on 27 July 2020).
50. Cheong, T.S.; Ko, I.; Labadie, J.W. Development of multi-objective reservoir operation rules for integrated water resources management. *J. Hydroinform.* **2010**, *12*, 185–200. [CrossRef]
51. Song, W.Z.; Yuan, Y.; Jiang, Y.Z.; Lei, X.H.; Shu, D.C. Rule-based water resource allocation in the Central Guizhou Province, China. *Ecol. Eng.* **2016**, *87*, 194–202. [CrossRef]
52. Divakar, L.; Babel, M.S.; Perret, S.R.; Gupta, A. Das Optimal allocation of bulk water supplies to competing use sectors based on economic criterion—An application to the Chao Phraya River Basin, Thailand. *J. Hydrol.* **2011**, *401*, 22–35. [CrossRef]
53. Muller, J. *Estimating the Marginal Value of Agricultural Irrigation Water*; University of Cape Town: Cape Town, South Africa, 2016. Available online: https://open.uct.ac.za/handle/11427/25409 (accessed on 19 August 2020).
54. Oxley, R.L.; Mays, L.W. Application of an Optimization Model for the Sustainable Water Resource Management of River Basins. *Water Resour. Manag.* **2016**, *30*, 4883–4898. [CrossRef]
55. Sjöstrand, K.; Lindhe, A.; Söderqvist, T.; Rosén, L. Sustainability assessments of regional water supply interventions—Combining cost-benefit and multi-criteria decision analyses. *J. Environ. Manage.* **2018**, *225*, 313–324. [CrossRef]
56. Sjöstrand, K. Water management—Decision support for informed prioritizations. In Proceedings of the 4th Water Research Commission Symposium, Johannesburg, South Africa, 11–13 September 2019.
57. The Office of the Chief Economic Adviser: Scottish Government. Computable General Equilibrium (CGE) Modelling and SG's CGE Model. 2015. Available online: https://www.gov.scot/publications/cge-modelling-introduction/ (accessed on 7 August 2020).

58. Burfisher, M.E. Introduction to Computable General Equilibrium Models. In *Introduction to Computable General Equilibrium Models*; Cambridge University Press: Cambridge, UK, 2017; pp. 8–23. Available online: https://www.cambridge.org/core/product/identifier/CBO9781316450741A014/type/book_part (accessed on 10 March 2021).
59. Zhang, Y.; Lu, Y.; Zhou, Q.; Wu, F. Optimal water allocation scheme based on trade-offs between economic and ecological water demands in the Heihe River Basin of Northwest China. *Sci. Total Environ.* **2020**, *703*, 134958. [CrossRef] [PubMed]
60. Degefu, D.M.; He, W.; Yuan, L.; Zhao, J.H. Water Allocation in Transboundary River Basins under Water Scarcity: A Cooperative Bargaining Approach. *Water Resour. Manag.* **2016**, *30*, 4451–4466. [CrossRef]
61. Mehrparvar, M.; Ahmadi, A.; Safavi, H.R. Social resolution of conflicts over water resources allocation in a river basin using cooperative game theory approaches: A case study. *Int. J. River Basin Manag.* **2016**, *14*, 33–45. [CrossRef]
62. Etro, F. Research in economics and game theory. A 70th anniversary. *Res. Econ.* **2017**, *71*, 1–7. [CrossRef]
63. Oftadeh, E.; Shourian, M.; Saghafian, B. An Ultimatum Game Theory Based Approach for Basin Scale Water Allocation Conflict Resolution. *Water Resour. Manag.* **2017**, *31*, 4293–4308. [CrossRef]
64. Yuan, L.; He, W.; Degefu, D.M.; Liao, Z.; Wu, X. Water allocation model in the lancing-mekong river basin based on bankruptcy theory and bargaining game. In Proceedings of the World Environmental and Water Resources Congress 2017, Sacramento, CA, USA, 21–25 May 2017; pp. 628–642. [CrossRef]
65. Madani, K.; Pierce, T.W.; Mirchi, A. Serious games on environmental management. *Sustain. Cities Soc.* **2017**, *29*, 1–11. [CrossRef]
66. Madani, K. Game theory and water resources. *J. Hydrol.* **2010**, *381*, 225–238. [CrossRef]
67. Bahrini, A.; Riggs, R.J.; Esmaeili, M. Social choice rules, fallback bargaining, and related games in common resource conflicts. *J. Hydrol.* **2021**, *602*, 126663. [CrossRef]
68. Ananda, J.; Herath, G. A critical review of multi-criteria decision making methods with special reference to forest management and planning. *Ecol. Econ.* **2009**, *68*, 2535–2548. [CrossRef]
69. Sarband, E.M.; Araghinejad, S.; Attari, J. Developing an Interactive Spatial Multi-Attribute Decision Support System for Assessing Water Resources Allocation Scenarios. *Water Resour. Manag.* **2020**, *34*, 447–462. [CrossRef]
70. Cai, X.; Lasdon, L.; Michelsen, A.M. Group decision making in water resources planning using multiple objective analysis. *J. Water Resour. Plan. Manag.* **2004**, *130*, 4–14. [CrossRef]
71. Ahmad, I.; Tang, D. Multi-objective Linear Programming for Optimal Water Allocation Based on Satisfaction and Economic Criterion. *Arab. J. Sci. Eng.* **2016**, *41*, 1421–1433. [CrossRef]
72. Gunantara, N. A review of multi-objective optimization: Methods and its applications. *Cogent Eng.* **2018**, *5*, 1502242. [CrossRef]
73. Nasiri-Gheidari, O.; Marofi, S.; Adabi, F. A robust multi-objective bargaining methodology for inter-basin water resource allocation: A case study. *Environ. Sci. Pollut. Res.* **2018**, *25*, 2726–2737. [CrossRef]
74. Dadmand, F.; Naji-Azimi, Z.; Motahari Farimani, N.; Davary, K. Sustainable allocation of water resources in water-scarcity conditions using robust fuzzy stochastic programming. *J. Clean. Prod.* **2020**, *276*, 123812. [CrossRef]
75. Mirchi, A.; Madani, K.; Watkins, D.; Ahmad, S. Synthesis of system dynamics tools for holistic conceptualization of water resources problems. *Water Resour. Manag.* **2012**, *26*, 2421–2442. [CrossRef]
76. Cunha, A.; Morais, D. Decision Support Model for Participatory Management of Water Resource. *Springer Int. Publ. Switz.* **2015**, *216*, 85–97. [CrossRef]
77. Smith, C.M.; Shaw, D. The characteristics of problem structuring methods: A literature review. *Eur. J. Oper. Res.* **2019**, *274*, 403–416. [CrossRef]
78. Martínez-Santos, P.; Henriksen, H.J.; Zorrilla, P.; Martínez-Alfaro, P.E. Comparative reflections on the use of modelling tools in conflictive water management settings: The Mancha Occidental aquifer, Spain. *Environ. Model. Softw.* **2010**, *25*, 1439–1449. [CrossRef]
79. He, Y.; Chen, X.; Sheng, Z.; Lin, K.; Gui, F. Water allocation under the constraint of total water-use quota: A case from Dongjiang River Basin, South China. *Hydrol. Sci. J.* **2018**, *63*, 154–167. [CrossRef]
80. Keskinen, M.; Käkönen, M.; Tola, P.; Varis, O. The Tonle Sap Lake, Cambodia: Conflicts With Abundance of Water. *Econ. Peace Secur. J.* **2007**, *2*, 49–59. Available online: https://www.epsjournal.org.uk (accessed on 12 November 2019).
81. Wang, Z.; Zheng, H.; Wang, X. A Harmonious Water Rights Allocation model for Shiyang River Basin, Gansu Province, China. *Int. J. Water Resour. Dev.* **2009**, *25*, 355–371. [CrossRef]
82. Gallego-Ayala, J. Trends in integrated water resources management research: A literature review. *Water Policy* **2013**, *15*, 628–647. [CrossRef]
83. Fu, Q.; Li, T.; Cui, S.; Liu, D.; Lu, X. Agricultural Multi-Water Source Allocation Model Based on Interval Two-Stage Stochastic Robust Programming under Uncertainty. *Water Resour. Manag.* **2018**, *32*, 1261–1274. [CrossRef]
84. Furlong, C.; Dobbie, M.; Morison, P.; Dodson, J.; Pendergast, M. *Infrastructure and Urban Planning Context for Achieving the Visions of Integrated Urban Water Management and Water Sensitive Urban Design*; Approaches to Water Sensitive Urban Design; Elsevier Inc.: Oxford, UK, 2018; pp. 329–350. [CrossRef]
85. Furlong, C.; Brotchie, R.; Considine, R.; Finlayson, G.; Guthrie, L. Key concepts for Integrated Urban Water Management infrastructure planning: Lessons from Melbourne. *Util. Policy* **2017**, *45*, 84–96. [CrossRef]
86. Nieuwoudt, W.L.; Backeberg, G.R. A review of the modelling of water values in different use sectors in South Africa. *Water SA* **2011**, *37*, 703–710. [CrossRef]

87. Li, M.; Guo, P.; Singh, V.P. An efficient irrigation water allocation model under uncertainty. *Agric. Syst.* **2016**, *144*, 46–57. [CrossRef]
88. Mathieu, L.; Tinch, R.; Provins, A. Catchment management in England and Wales: The role of arguments for ecosystems and their services. *Biodivers. Conserv.* **2018**, *27*, 1639–1658. [CrossRef]
89. Zhang, Y.F.; Li, Y.P.; Huang, G.H.; Ma, Y. A copula-based stochastic fractional programming method for optimizing water-food-energy nexus system under uncertainty in the Aral Sea basin. *J. Clean. Prod.* **2021**, *292*, 126037. [CrossRef]
90. Mannan, M.; Al-Ansari, T.; Mackey, H.R.; Al-Ghamdi, S.G. Quantifying the energy, water and food nexus: A review of the latest developments based on life-cycle assessment. *J. Clean. Prod.* **2018**, *193*, 300–314. [CrossRef]
91. Ren, C.; Xie, Z.; Zhang, Y.; Wei, X.; Wang, Y.; Sun, D. An improved interval multi-objective programming model for irrigation water allocation by considering energy consumption under multiple uncertainties. *J. Hydrol.* **2021**, *602*, 126699. [CrossRef]
92. Fan, J.L.; Kong, L.S.; Wang, H.; Zhang, X. A water-energy nexus review from the perspective of urban metabolism. *Ecol. Modell.* **2019**, *392*, 128–136. [CrossRef]
93. Mabhaudhi, T.; Nhamo, L.; Mpandeli, S.; Nhemachena, C.; Senzanje, A.; Sobratee, N.; Chivenge, P.P.; Slotow, R.; Naidoo, D.; Liphadzi, S.; et al. The water–energy–food nexus as a tool to transform rural livelihoods and well-being in Southern Africa. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2970. [CrossRef] [PubMed]
94. Zeng, X.; Zhao, J.; Wang, D.; Kong, X.; Zhu, Y.; Liu, Z.; Dai, W.; Huang, G. Scenario analysis of a sustainable water-food nexus optimization with consideration of population-economy regulation in Beijing-Tianjin-Hebei region. *J. Clean. Prod.* **2019**, *228*, 927–940. [CrossRef]
95. Kondili, E.; Kaldellis, J.K.; Papapostolou, C. A novel systemic approach to water resources optimisation in areas with limited water resources. *Desalination* **2010**, *250*, 297–301. [CrossRef]
96. Abdulbaki, D.; Al-Hindi, M.; Yassine, A.; Abou Najm, M. An optimization model for the allocation of water resources. *J. Clean. Prod.* **2017**, *164*, 994–1006. [CrossRef]
97. Su, D.; Zhang, Q.H.; Ngo, H.H.; Dzakpasu, M.; Guo, W.S.; Wang, X.C. Development of a water cycle management approach to Sponge City construction in Xi'an, China. *Sci. Total Environ.* **2019**, *685*, 490–496. [CrossRef]
98. Ben-Daoud, M.; Mahrad, B.E.; Elhassnaoui, I.; Moumen, A.; Sayad, A.; ELbouhadioui, M.; Moroșanu, G.A.; El Mezouary, L.; Essahlaoui, A.; Eljaafari, S. Integrated water resources management: An indicator framework for water management system assessment in the R'Dom Sub-basin, Morocco. *Environ. Chall.* **2021**, *3*, 100062. [CrossRef]
99. Rouillard, J.; Rinaudo, J.D. From state to user-based water allocations: An empirical analysis of institutions developed by agricultural user associations in France. *Agric. Water Manag.* **2020**, *239*, 106269. [CrossRef]
100. Toxopeüs, M.; Helen, S.F. Water Governance I: A Broad Outline of the Legislative Framework in South Africa. 2019. Available online: https://hsf.org.za/publications/hsf-briefs/water-governance-i-a-broad-outline-of-the-legislative-framework-in-south-africa (accessed on 13 March 2020).
101. Schreiner, B. Viewpoint—Why has the South African National Water Act been so difficult to implement? *Water Altern.* **2013**, *12*, 38–41. Available online: https://www.wrc.org.za/wp-content/uploads/mdocs/14%20Water%20law%20p%2038-41.pdf (accessed on 15 March 2020).
102. Pienaar, G.W.; Hughes, D.A. Linking Hydrological Uncertainty with Equitable Allocation for Water Resources Decision-Making. *Water Resour. Manag.* **2017**, *31*, 269–282. [CrossRef]
103. Dixon, P.B.; Jorgenson, D.W. *Handbook of Computable General Equilibrium Modeling*; Elsevier B.V.: Oxford, UK, 2013; ISBN 978-0-444-53634-1.
104. Roffe, S.J.; Fitchett, J.M.; Curtis, C.J. Classifying and mapping rainfall seasonality in South Africa: A review. *S. Afr. Geogr. J.* **2019**, *101*, 158–174. [CrossRef]
105. Di, D.; Wu, Z.; Wang, H.; Huang, S. Multi-objective optimization for water allocation of the Yellow River basin based on fluid mechanics, emergy theory, and dynamic differential game. *J. Clean. Prod.* **2021**, *312*, 127643. [CrossRef]
106. Yao, L.; Xu, Z.; Chen, X. Sustainable water allocation strategies under various climate scenarios: A case study in China. *J. Hydrol.* **2019**, *574*, 529–543. [CrossRef]
107. ISO 14040:2006. Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006. Available online: https://www.iso.org/obp/ui/#iso:std:iso:14040:%0Aed-2:v1:en (accessed on 19 August 2020).
108. Department of Water Affairs and Forestry. *National Water Resource Strategy*, 1st ed.; Department of Water Affairs and Forestry: Pretoria, South Africa, 2004. Available online: https://cer.org.za/wp-content/uploads/2017/10/NWRS-2004.pdf (accessed on 19 August 2020).
109. Basson, M.S.; Allen, R.B.; Pegram, G.G.S.; van Rooyen, J.A. *Probablistic Management of Water Resource and Hydropower Systems*; Water Resources Publications: Highlands Ranch, CO, USA, 1994.
110. Republic of South Africa. National Water Act, No 36 of 1998. Government Gazette 1998. Available online: https://www.gov.za/sites/default/files/gcis_document/201409/a36-98.pdf (accessed on 12 August 2020).
111. Tempelhoff, J. The Water Act, No. 54 of 1956 and the first phase of apartheid in South Africa (1948–1960). *Water Hist.* **2017**, *9*, 189–213. [CrossRef]
112. Rawlins, J. Political economy of water reallocation in South Africa: Insights from the Western Cape water crisis. *Water Secur.* **2019**, *6*, 100029. [CrossRef]

113. Muller, M. South Africa needs good water management—Not new water laws. *Conversation*. 2018. Available online: https://theconversation.com (accessed on 19 August 2019).
114. Herrfahrdt-Pähle, E. Applying the concept of fit to water governance reforms in South Africa. *Ecol. Soc.* **2014**, *19*, 25. [CrossRef]
115. Department of Water Affairs and Forestry. Water Allocation Reform Strategy. 2008. Available online: https://www.dws.gov.za/WAR/beneficial.aspx (accessed on 19 August 2019).
116. du Plessis, A. *Freshwater Challenges of South Africa and Its Upper Vaal River: Current State and Outlook*; Springer: Cham, Switzerland, 2017; pp. 65–76. [CrossRef]
117. Mclachlan, A. The balancing act of Gauteng's water security. *Water Wheel* **2020**, *19*, 38–42.
118. Coleman, T.J.; Mckenzie, R.S.; Rademeyer, J.I.; Van Rooyen, P.G. Lessons learned from the Vaal river system reconciliation strategy study. In Proceedings of the 13th SANCIAHS Symposium, Cape Town, South Africa, 5–7 September 2007.
119. Munnik, V. *The Reluctant Roll-Out of Catchment Management Agencies (Report to Water Research Commission)*; Water Research Commission: Pretoria, South Africa, 2020.
120. Paterson, M.N. Exploring the role of Cooperative Governance in Water Resource Management: A study of Catchment Management Agencies in South Africa. 2022. Available online: https://scholar.sun.ac.za (accessed on 12 May 2022).
121. Van Rooyen, P.G.; Mckenzie, R.S.; Rademeyer, J.I. *Lessons Learned from Three Decades of Water Resource Planning of the Integrated Vaal River System*; WRP Consulting Engineers (Pty) Ltd.: Pretoria, South Africa, 2018.