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Evaluation of Future-Integrated Urban Water Management Using a Risk and Decision Analysis Framework: A Case Study in Denver–Colorado Metro Area (DCMA)

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Abstract: This study examines the DCMA concerning the future risk of the water security status. We considered three risk factors: population growth, economic growth, and natural water supply–demand differences. In the risk analysis part, we consulted with experts from several sectors including academia, Non-Governmental Organizations (NGOs), and industry, to predict that the probability of future water stresses in high-, medium-, and low-risk scenarios are 0.73, 0.24, and 0.03, respectively. In the decision analysis part, we adopted two multiple criteria decision analysis (MCDA) approaches that include multiple attribute value theory (MAVT) and analytic hierarchy process (AHP) methods to evaluate the best alternative decision to alleviate future water stresses in the DCMA. The sensitivity analysis demonstrates that, although expanding existing water reservation might be a solution to tackle the challenge, the best option really closely connects to the weighting scheme of the criteria considered in the framework. This study provides a valuable risk and decision analysis framework to analyze the water security status associated with the future water supply and demand gap decrease caused by three risk factors: population growth, climate change, and natural water supply.

Keywords: water supply and demand; risk analysis; decision analysis; climate change; multiple criteria decision analysis (MCDA); Denver–Colorado Metro Area (DCMA)

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1. Introduction

Water scarcity and drought have been severe problems for Colorado state historically. It is reported that the Colorado River basin is one of the most highly water-stressed places in the world [1]. Although the improved water management strategy has relieved the state's water usage stresses, the region is still likely to suffer from future water shortages [2]. Combined with recent population growth, economic expansion, as well as climate change, it is believed that water stresses will be one of the most critical threats to all Colorado people without an appropriate integrated urban water management strategy. Thus, developing an urban water management strategy and analyzing future water resource risks under climate and anthropogenic risk factors is imperative for local decision makers.

Population growth increases water scarcity. In the 2018 edition of the United Nations (UN) World Water Development Report (WWDR), they predicted that nearly 6 billion people will likely suffer from clean water scarcity by 2050 [3]. This is because the population will demand more clean water access and cause a higher probability of water pollution simultaneously, which can enlarge the water supply and demand gap. Driven by the interlinkage between population expansion, economic growth, and water pollution, Boretti and Rosa [4] further discussed the idea that the water scarcity situation may be even worse than what was presented in the 2018 report. In terms of the Colorado River basin region, Richter [5] found that cities that depend on the Colorado River and its tributaries are significantly reducing their per capita water usage to adapt to the dilemma between the growing needs of clean water resources and declining reservoir levels. They pointed out that opportunity may exist to develop better water management strategies for the region, such as increasing utility usage of other water sources consisting of water reuse, desalination, and stormwater capture to reduce pressure on the Colorado River Basin if per capita water usage rates continue to decline [5]. With more uncertainties in future anthropogenic activity factors, similar results can also be identified in Hung et al. [6].

Additionally, climate change plays a critical role in determining future water stresses. Previous studies have identified the importance of regional climate change to local water supply, such as precipitation [7]. For example, He and Ding [7] adopted a global climate model–regional climate model (GCM-RCM) to recognize the importance of regional climate change, that will significantly impact the natural water supply to an area, leading to severe water stresses or even extreme weather events like drought. Meanwhile, the works of He [8] and He et al. [9] pointed out that climate change can also cause water-related climate disasters, such as inland waterway floods, leading to higher social vulnerability in a region. Thus, it is believed that climate change closely connects to a region's water-related climatic system that directly determines its water security and vulnerabilities. Additionally, a previous study also identified a strong relationship between urban water stress risks and the water–energy–food (WEF) nexus [10]. Similarly, research has a long history of identifying the relationship between the effects of climate change on the water resources of the Colorado River basin [11]. For example, the study by Christensen et al. [11] evaluated the potential effects of climate change on the hydrology and water supply of the Colorado River Basin by comparing simulated hydrologic and water resources scenarios derived from downscaled climate simulations of the Department of Energy (DoE). It illustrated that future temperature increase is a critical reason for the reduction in future basin storage [11].

Fault tree analysis (FTA) was adopted in the risk analysis section. Here, the FTA is a top–down method based on future water stress scenarios that begins with each risk factors that include population growth, climate change, and natural water supply and demand. By assigning prior distributions to each of the scenarios associated with the risk factors identified in the study, it provides a valuable framework for obtaining vital information regarding the uncertainties of the occurrence of low-, medium-, and high-risk events. In summary, the aim of using FTA in this study was to (1) develop a clear pathway to illustrating the relationship between risk factors and future water resources scenarios; (2) quantify the probability of events associated with each future water resources scenario; (3) quantify the conditional probability of the future water risk rating to determine the most critical risk factor. Thus, the FAT analysis is a simple and good tool to systematically evaluate and understand the potential risk of the future water system, and results from risk analysis have guiding significance in subsequent decision analyses.

Multiple criteria decision analysis (MCDA) has been adopted in previous studies to support clean water resources management [12]. For example, Peters et al. [12] adopted multiple MCDA approaches to assess the probable success of these drinking water sources based on various technical, economic, social, and environmental factors across numerous stakeholders that include locals, Non-Governmental Organizations, and ecological science academies in Southwestern Bangladeshi communities. They included the multiple attribute value theory (MAVT) and analytic hierarchy process (AHP) to inform the preferences from three stakeholders to ensure proper weighting of criteria for success. While their case study demonstrated how decision modeling and alternative evaluation can be an excellent first step in analyzing complicated water management problems, they did not incorporate any risk analyses in the evaluation framework. A similar adoption of AHP can also be found in the research carried out by Bognár and Benedek [13]; here, a new AHP-incorporated AHP-PRISM (partial risk map) method was developed to evaluate a real-life case study of a nuclear power plant. Also, in research by Zhang et al. [14], the authors combined an AHP method and an improved version of the Criteria Importance Through Inter-Criteria Correlation (CRITIC) method to solve integrated evaluation problems related to the service status of groins in waterways. Additionally, as in the research of He and Guan [15], such studies have exhibited the importance of combining risk analysis and decision analysis as a comprehensive framework for evaluating an environmental justice problem. Similar frameworks can also be applied in water management strategies. Although He and Guan [15] developed a risk and analysis framework to evaluate future air quality risk in the Los Angeles–Long Beach Metro Area (LA-LBMA), they only adopted a single approach of MCDA: multiple attribute value theory (MAVT). This was used in the decision analysis part, making the whole framework oversimplified rather than sophisticated. In this study, we want to incorporate these two methods—MAVT and AHP—in the decision analysis part to illustrate how simple decision tools can help decision makers in accelerating the process of assessing possible alternatives to alleviate future water stresses.

Thus, the objective of this study is to develop a comprehensive risk and decision analysis framework to evaluate the integrated urban water management strategy in the Colorado–Denver Metro Area (CDMA). Specifically, we compared two MCDA approaches in the decision analysis section that include multiple attribute value theory (MAVT) and analytic hierarchy process (AHP) methods. The rest of the paper is organized as follows. Section 2 elaborates on the methodology of the risk and decision analysis framework developed in this study to assess the integrated urban water management strategy. Next, Section 3 illustrates the results and discussions associated with the developed risk and decision analysis framework's application in the CDMA integrated urban water management strategy. Finally, Section 4 delivers some of the conclusions and future research directions.

2. Methods

We combined risk and decision analysis in this framework to evaluate an integrated water management strategy in our study area – Denver Colorado Metro Area (DCMA) (Figure 1). Additionally, a sensitivity analysis was incorporated to assess the stakeholder's best interest based on different subjective criteria preferences. Figure 2 shows the multiple criteria decision analysis (MCDA) process combined with the risk analysis framework adopted in this study.

2.1. Study Area

In this study, we choose the Denver-Colorado Metro Area (DCMA) to serve as the study area because many studies have identified a severe possible water shortage scenario under the ongoing climate change circumstance for the area [11,16]. Thus, the urban water management strategy in the DCMA has a rich history of being studied [17]. The Denver–Aurora–Lakewood–Colorado Metro Area consists of ten Colorado counties, including the City and County of Denver, Arapahoe County, Jefferson County, Adams County, Douglas County, the City and County of Broomfield, Elbert County, Park County, Clear Creek County, and Gilpin County. These have a total of population over 2.96 million as of 2020 [18]. Here, two major water providers in the DCMA are focused on the following integrated urban water strategy management analysis: Aurora Water and Dominion Water (Figure 1). Figure 1 is adapted from Denver Water: Water, Infrastructure and Supply Efficiency (WISE: https://www.denverwater.org/your-water/water-supply-and-planning/wise (accessed on 11 November 2023).

Aurora water is the most critical water supply to Colorado's third largest city, the City of Aurora. Aurora Water's initiative, the Prairie Waters Project (PWP), is a testament to the city's proactive approach toward securing a sustainable water supply [19]. Given its vision to accommodate future growth while recognizing its limitations, the incorporation of diverse water resources and the pursuit of strategic partnerships are commendable. The city's reliance on senior water rights highlights its long-term commitment to ensuring a stable water supply. At the same time, its collaboration with the WISE (2012) partnership reflects its willingness to support neighboring regions during the interim period.

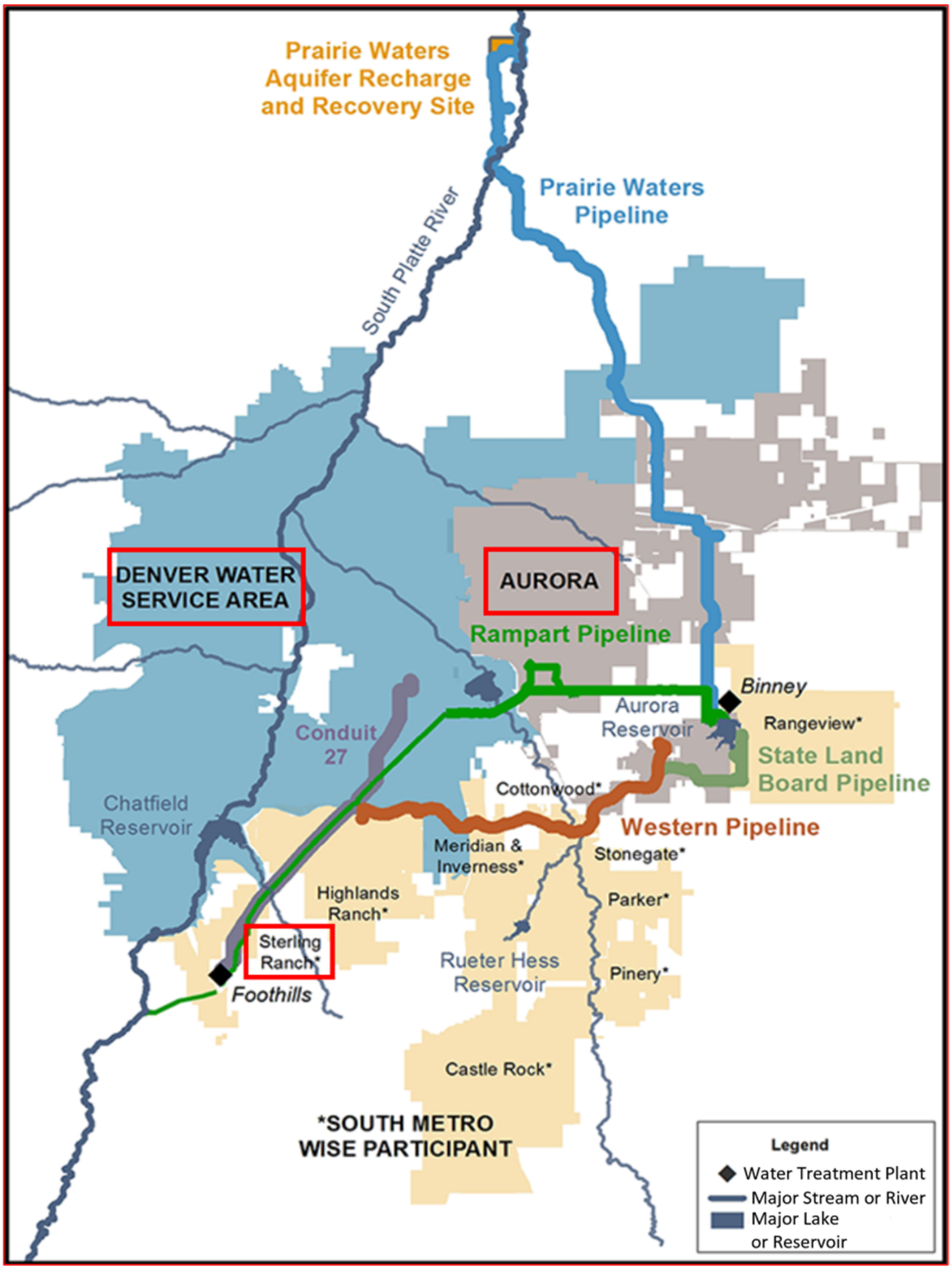


Figure 1. Study area—Denver–Colorado Metro Area (DCMA).

However, the financial constraints that Aurora faces underscore the importance of balanced financial planning and debt management. As the city prepares to cater to the needs of a growing population and to potentially support the water requirements of other regions, it becomes crucial to maintain a sustainable financial trajectory. Exploring alternative funding mechanisms or optimizing existing resources could possibly alleviate some of the financial burden, ensuring that the city can continue its water management endeavors without compromising its fiscal stability.

Dominion Water is a relatively new water supplier in Douglas County that was formed to serve the needs of Sterling Ranch. Sterling Ranch is a new development in the northwest corner of Douglas County that was home to some 12,050 residences by 2020, in addition to commercial, school, and medical space. Over the last decade, Sterling Ranch and Dominion Water have studied water supply and demand needs associated with the new development. Sterling Ranch exists in an area previously not served by water utilities. This is mainly because water rights in Douglas County are fully encumbered (there are no remaining rights for new developments), which precludes new developers from acquiring water supply unless they can purchase the rights from the existing owners [20]. Additionally, we also include the municipal water plan comparison summary of the state level [21] in the supplementary material.

In conclusion, several key points are noteworthy in understanding the clean water dynamics in the DCMA:

1. Water rights limitations: The critical issue of fully encumbered water rights in Douglas County has created a barrier to new developments in acquiring water supply. Without the possibility of accessing additional rights, new developers must resort to alternative strategies to meet the water demand of their projects.
2. Reliance on groundwater: Douglas County's heavy reliance on groundwater, particularly from the Denver Basin Aquifer, poses sustainability challenges due to its limited or negligible annual recharge. Decreasing this dependence is contingent on the exploration of new surface water resources.
3. Diversified water management approaches: Dominion Water has adopted a multi-pronged approach to meet the water demand of Sterling Ranch. This includes utilizing junior rights to surface flows, reclaimed effluent, groundwater, potential rainwater harvesting, and the purchase of WISE water, reflecting a comprehensive strategy that integrates multiple water sources.
4. WISE partnership [22]: The Water Infrastructure Supply and Efficiency partnership, involving Aurora Water, Denver Water, and several communities in the Douglas County South Metro Water Supply Authority, including Dominion Water, highlights the collaborative effort to manage and distribute water resources efficiently. This intergovernmental agreement aims to optimize the use of water resources and ensure that excess water from Aurora and Denver is made available to other participating communities.
5. Long-term implications: While developers and water providers initially bear the capital risk, the long-term implications of water management fall on customers who will face potential challenges related to utilities and fees.

2.2. Risk Analysis

Figure 2 displays the risk and decision analysis framework developed in this study. In the risk analysis section, we first defined decision goals, constraints, alternatives, and criteria to guide the construction of the risk factors analysis. For example, we devised the decision analysis framework based on the probability of future water security scenarios in this study. Thus, we consider several risk factors—including population growth, climate change, and natural water supply and demand—that can be used to determine the probability of risk structure of the region's future water security (Figure 2). Specifically, we consulted several expert's opinions as well as the Global Climate Model (GCM–Regional Climate Model (RCM) simulations to help construct the cumulative distribution function (CDF) of those risk factors. In this study, a total of 30 experts from academia, Non-Governmental Organizations (NGOs), and industry were consulted. Additionally, a total of 8 CMIP6 GCM-RCM climate models were consulted to evaluate the risk of future climate change for the area. Detailed information regarding the experts and climate models' consultation is summarized in the Supplementary Materials.

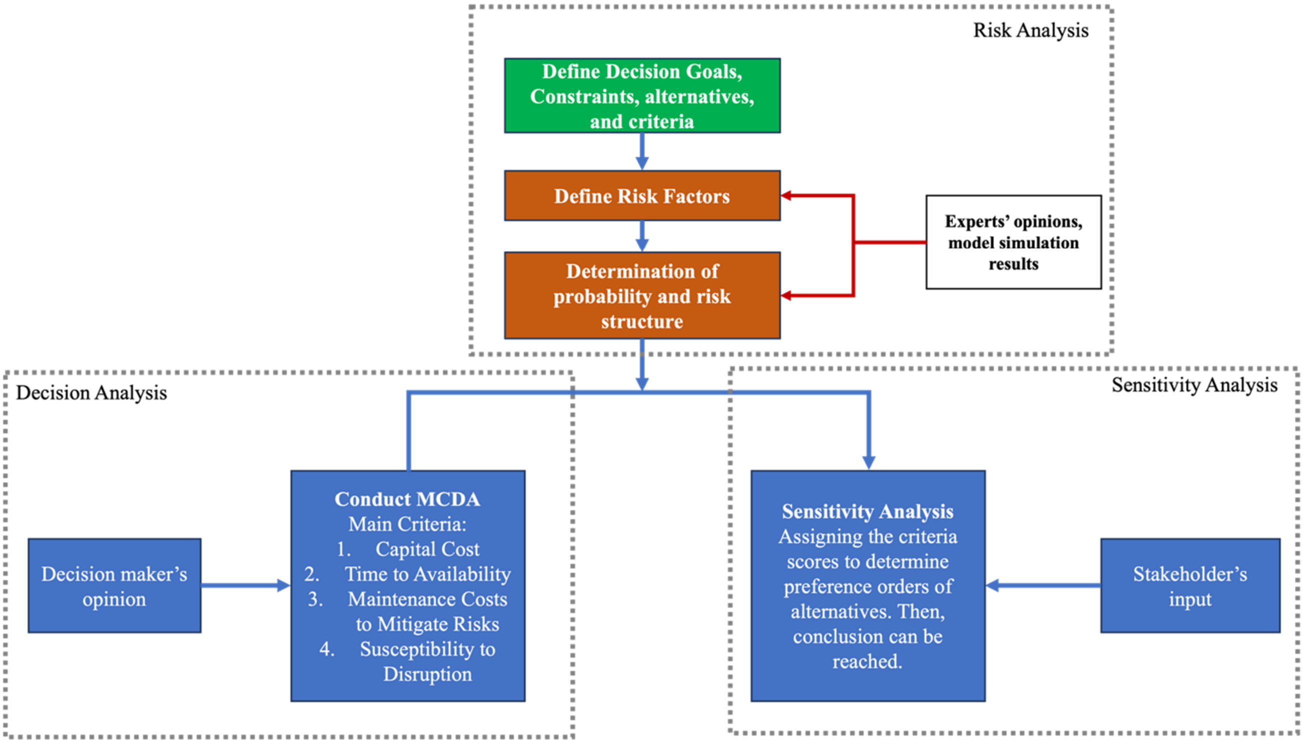


Figure 2. Risk and decision analysis associated with integrated urban water management studied in this study.

Additionally, we adopted the event tree approach to manage the uncertainty analysis of the future water security scenarios (Figure 3). The probability of the future water security scenario was calculated based on each risk factor (Figure 3). Specifically, we constructed three scenarios for each risk factor that include the increase, decrease, and no-change scenarios. Additionally, the probability of each scenario was assigned for each risk factor based on the CDF information associated with each risk factor. Finally, the probability distribution of future water security scenarios can be evaluated based on the probability distribution of each risk factor and their combinations. Detailed information of the calculation results is elaborated in the following results section.

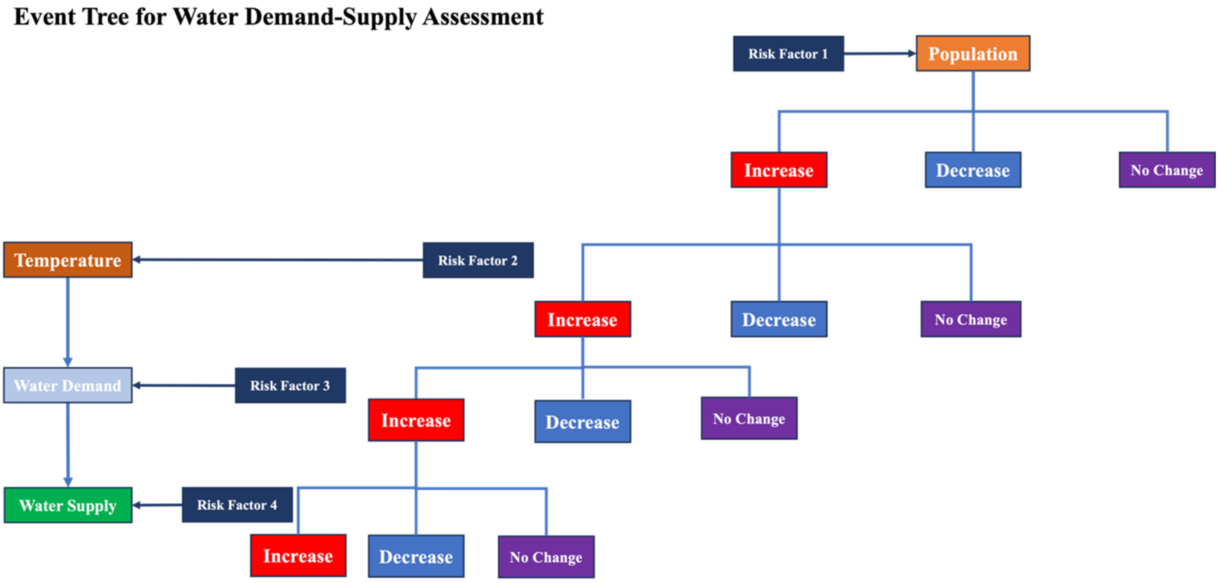


Figure 3. Event tree for the assessment of future water demand–supply management.

2.3. Decision Analysis

We constructed the decision analysis framework and investigated two MDCA approaches: multiple attribute value theory (MAVT) and analytic hierarchy process (AHP). Additionally, we conducted a sensitivity analysis to illustrate how decision alternatives can be perceived and assessed based on different criterion weighting spaces. Here, we first briefly review the multiple attribute value theory (MAVT) and analytic hierarchy process (AHP) methods adopted in this study.

2.3.1. Multiple Attribute Value Theory (MAVT)

MAVT is a popular method to quantitatively assess the performance of alternative decisions. Specifically, each decision alternative's total score is assigned a weighted summation:

$$u_i = \sum_{n=1}^{m} a_{i,n} b_n \tag{1}$$

In Equation (1), the alternative's total score u_i is a summation of the products between weights b_n for the nth criterion and the normalized performance scores $a_{i,n}$ for the decision alternative i. The weights variable b_n ranges from 0 to 1 and follows the total sum, equal to one rule: $\sum_{n=1}^{m} b_n = 1$. Additionally, the variable $a_{i,n}$ is designed to range from 1 to m, based on the performance ranking of each attribute criterion. It should be noted that it is appropriate to assume mutual preferential independence between attributes that preference between any of two attributes is not influenced by the value of any of the other attributes [23].

2.3.2. Analytic Hierarchy Process (AHP)

The analytic hierarchy process (AHP) is a widely utilized pairwise comparison technique developed by Saaty [24,25]. It is commonly employed in decision-making processes that involve complex multiple criteria. AHP is especially useful when there is a need to prioritize and select from various alternatives in a structured and logical manner. The method helps to quantify subjective judgments, which are then used to derive priorities and make informed decisions.

The process involves constructing a hierarchical structure of decision criteria and alternatives, followed by pairwise comparisons of the elements within each level of the hierarchy. Saaty's [24] 9-point scale is typically used to assign values that represent the relative importance of one element compared to another. Comparisons are usually made in terms of how much more important one criterion is in comparison with another.

After the pairwise comparisons, the geometric mean of the elements is calculated, and the priorities are determined. The priorities of the higher-level criterion categories are used to weigh the criteria priorities, ultimately resulting in a global priority or weight for each criterion. These weights are then applied to the scores of the alternatives, aiding in decision making based on the derived priorities.

The use of AHP is particularly beneficial when dealing with complex decision-making scenarios that involve multiple criteria and alternatives. It allows decision makers to structure their judgments and preferences systematically, thus facilitating a more informed and rational decision-making process.

Here, for the sake of simplicity, we only briefly review the AHP process. For more comprehensive understanding and to implement the details of the AHP method, it is advisable to refer to the works of Thomas L. Saaty, such as "The Analytic Hierarchy Process" and "Decision Making for Leaders: The Analytical Hierarchy Process for Decisions in a Complex World" [24,25].

Compared with MAVT, AHP relies on pairwise comparisons to derive preference scales and may face challenges when dealing with many criteria and alternatives as MAVT is designed to handle more complex decision situations involving a large number of attributes and alternatives. Moreover, AHP may be more sensitive to the choice of weights assigned to criteria, and small changes in these weights can lead to different outcomes; this is because MAVT may be less sensitive to weight assignments because it often involves a more direct and explicit modeling of criteria preferences. Thus, combined with these two decision analysis modeling approaches in the decision analysis part, we believe that comprehensive modeling results can be delivered while keeping the modelling approaches simple.

3. Results and Discussion

3.1. Risk and Uncertainty Analysis

The approximated cumulative probability distributions of the three risk factors associated with future water stress in the DCMA are summarized in Figure 4. Population in the DCMA is expected to increase at a modest rate. The current annual population growth rate in the DCMA is around 1.2%/year [26]. Based on historical data and experts' assumptions as well as predictions, there is a 50% likelihood that the population increase rate will be larger than 0.44 by the year 2050 (Figure 4a).

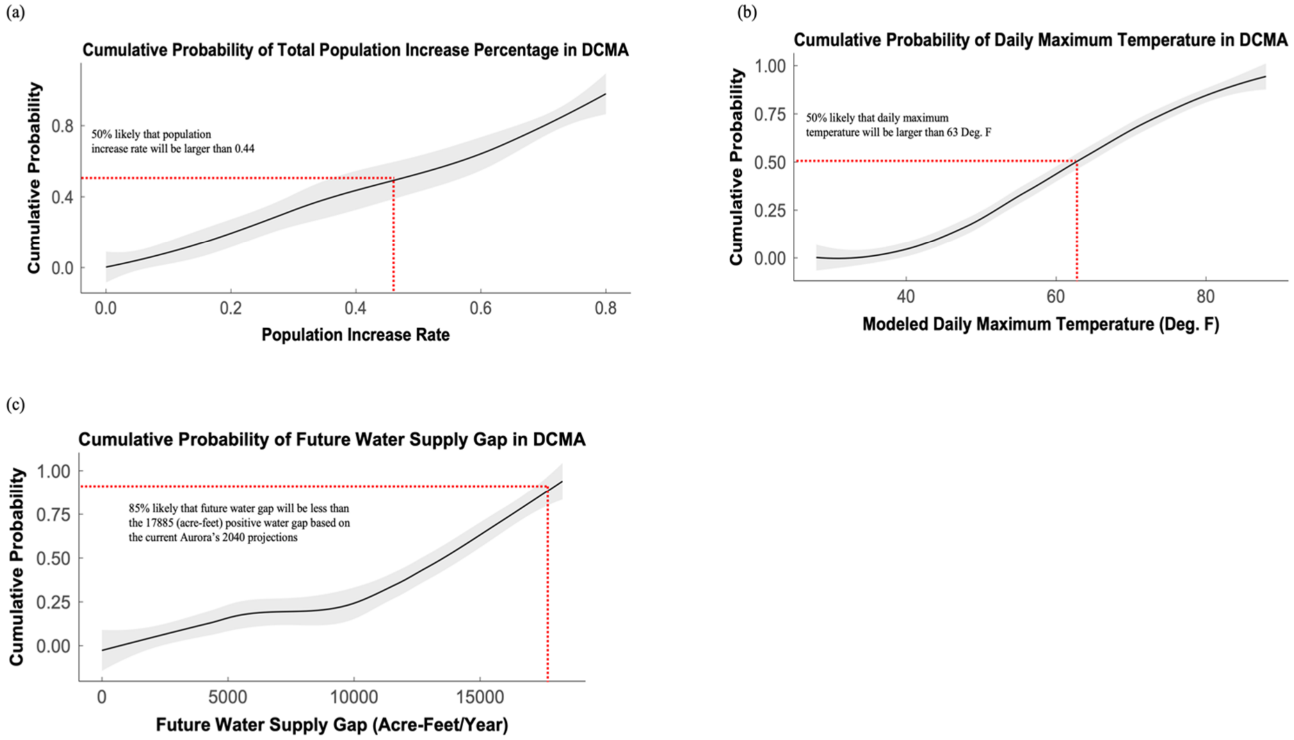


Figure 4. Cumulative probability distribution of three risk factors associated with future water stresses in DCMA: (**a**) cumulative probability of total population increase percentage in DCMA; (**b**) cumulative probability of daily maximum temperature (Deg. F) in DCMA; (**c**) cumulative probability of future water supply gap in DCMA.

Projected climate change was assessed based on daily maximum near-surface temperature from 2020 to 2050 in Fahrenheit degrees across 225 square miles of grids that cover the counties of Adams, Arapahoe, Denver, and Douglas. The U.S. Department of Energy (DOE) CMIP6 climate data were used to evaluate the changes in the daily maximum near-surface temperature changes across the grid's areas under moderate (RCP45) or conservative (RCP85) scenarios. Additionally, experts' opinions were consulted to construct the CDF of the temperature metric. Detailed information regarding the Global Climate Model–Regional Climate Model (GCM-RCM) selection and expert's consultation process are included in the Supplementary Materials. Based on the information of experts' opinions and model simulations, Figure 4b shows that there is 50% daily likelihood that the maximum temperature will be larger than 63 degrees Fahrenheit.

In terms of water supply and demand, given that the City of Aurora has conducted extensive studies comparing current and projected water needs and acts as the primary supplier for both Denver and Douglas County (Dominion Water) through augmentation, all calculations regarding supply and demand were based on Aurora. When a shortfall in water supply arises, it was assumed that water may not be accessible for use by Denver and Dominion. Consequently, all involved parties would have to employ existing and additional strategies for conserving and acquiring water. The projections for supply and demand are established according to Aurora's 2050 estimations, with an initial supply of 95,272 acre-feet and an initial demand of 77,389 acre-feet [19]. Also, experts provided sufficient information in this process to help construct the CDF of future water supply gap approximation shown in Figure 4c.

Based on these prior assumptions, we consulted with experts to define the change levels based on the average annual change rate of these risk factors and water supply–demand gap decreases. The detailed information regarding these definitions is summarized in Tables 1 and 2.

Table 1. Defined change level based on average annual change range of risk factors.

Future Water Supply–Demand Risk Factor		
	Decrease rate *	Decrease Level *
Gap (Acre-Feet/Year)	30–50%	High
	15–30%	Medium
	0–15%	Low
Factors	Increase Rate *	Definition of Increase Level *
Population	30–50%	High
	15–30%	Medium
	8–15%	Low
Temperature	2–3%	High
	1–2%	Medium
	0–1%	Low

Note(s): * We consulted experts' opinions regarding the definition of the change rate for each of these risk factors.

Table 2. Defined level of water supply–demand gap decreases within next 30 years.

Decrease Level	**Decrease Rate**	**Water Supply–Demand Gap Decrease**
High	50%	8943 (Acre-Feet/Year)
Medium	30%	5366 (Acre-Feet/Year)
Low	20%	2683 (Acre-Feet/Year)

A completed event tree using the information provided above is presented in Figure 5. Precisely, the probability of high, medium, and low scenarios of water supply–demand gap decrease is calculated as 0.73, 0.24, and 0.03, respectively. The advantage of the event tree is that it can exhibit the potential future pathways toward water security scenarios and the probability associated with each pathway. For instance, the high increase rate scenario for the population growth is defined as 30–50% based on Table 1. Meanwhile, Figure 4a can be consulted to derive the probability value for the high increase rate scenario for population growth risk factor, which is around 0.7. Similar calculations can be conducted to derive the probability of each scenario of the other risk factors. It should be noted that the final comprehensive probability of each scenario of future water stresses is summed up by all the probabilities of the paths corresponding to that scenario.

Figure 5. Complete event tree of future water security risk analysis.

Additionally, two conditional probabilities were calculated to determine the most critical risk factor in the future water security condition. Here, the scenario of a high decrease in water supply and demand gap is defined as the scenario of the most interest. Based on the calculation results shown in Table 3, climate change is the primary concern of the risk factor as it has the most significant probability of causing a high decrease in future water supply and demand gap in the DCMA compared to the other two risk factors.

Table 3. Conditional probability associated with future water risk rating.

P [Stress = High ∣ Risk Factor = (High, Medium, Low)]	P (Risk Factor = High ∣ Stress = High)
P (stress = high ∣ population growth = high) = 0.64	P (population growth = high ∣ stress = high) = 0.6147
P (stress = high ∣ population growth = medium) = 0.09	
P (stress = high ∣ population growth = low) = 0	
P (stress = high ∣ temperature increase = high) = 0.687	P (temperature increase = high ∣ stress = high) = 0.8012
P (stress = high ∣ temperature increase = medium) = 0.042	
P (stress = high ∣ temperature increase = low) = 0	
P (stress = high ∣ water supply–demand gap decrease = high) = 0.286	P (water supply–demand gap decrease = high ∣ stress = high) = 0.1373
P (stress = high ∣ water supply–demand gap decrease = medium) = 0.205	
P (stress = high ∣ water supply–demand gap decrease = low) = 0.238	

3.2. Decision Analysis

Figure 6 displays the influence diagram associated with the decision analysis evaluated in this study. The goal of the decision analysis is to evaluate the effectiveness of decision alternatives that can be investigated to alleviate future water stresses in DCMA, under the circumstances of the three risk factors identified in the risk analysis section. Based on a consultation with experts from multiple sectors, including academic institutions, NGOs, and industry sectors, we recognized a potential total of 10 decision selection criteria that are categorized into four sectors: economic, technical, environmental, and social aspects. These are shown in Figure 7. For simplicity, we only consider four decision criteria in this study: mean capital cost, mean time to be effective, maintenance cost to mitigate risks, and susceptibility to disruption. These are shown in Figure 6. These four decision criteria were chosen here because they are easy to understand and can be numerically quantified. Meanwhile, a total of three decision alternatives, including purchasing water rights, groundwater pumping and recharging, and expanding existing storage reservations, served as examples for elaborating the methodology in this study. In terms of the multiple criteria considered, the detailed information associated with each alternative and the estimated monetary cost for each decision alternative are summarized in Table 4. Specifically, the monetary cost range for each decision alternative is estimated based on the defined level of water supply–demand gap decrease, as summarized in Table 2. For example, the monetary cost range of each selected decision alternative can be obtained through a multiplication between the estimated water gap amount associated with each scenario and the estimated mean capital cost associated with that specific alternative decision. Following this, based on the monetary cost of each decision alternative, valuation ranges and the ranking of each decision alternative were determined based on a consultation with experts (Table 5). Thus, alternative decisions can be evaluated and compared based on the decision analysis approaches selected. Here, to assess the effectiveness of the decision alternatives, two approaches were adopted in this study: MAVT and AHP.

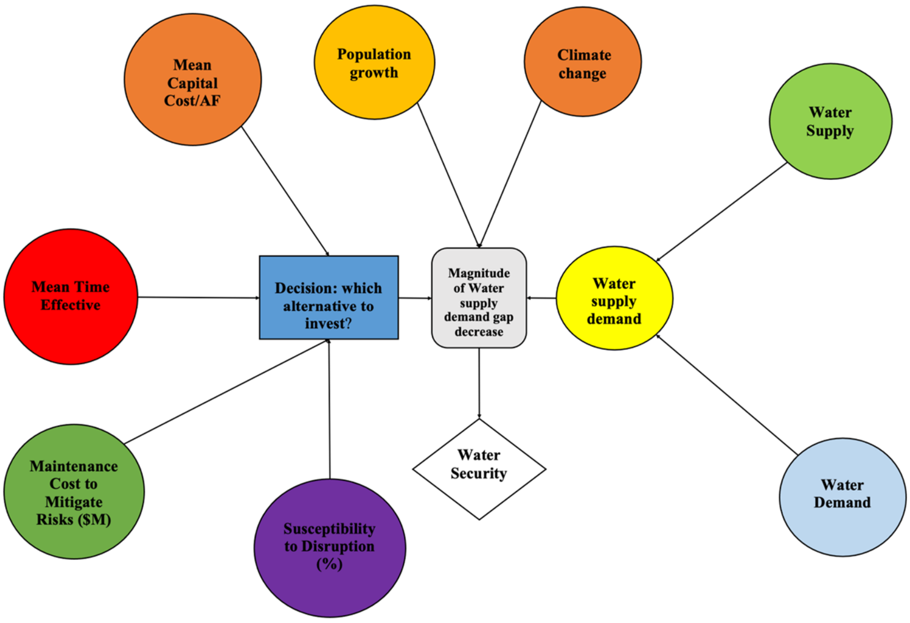


Figure 6. Influence diagram associated with quantitative decision analysis.

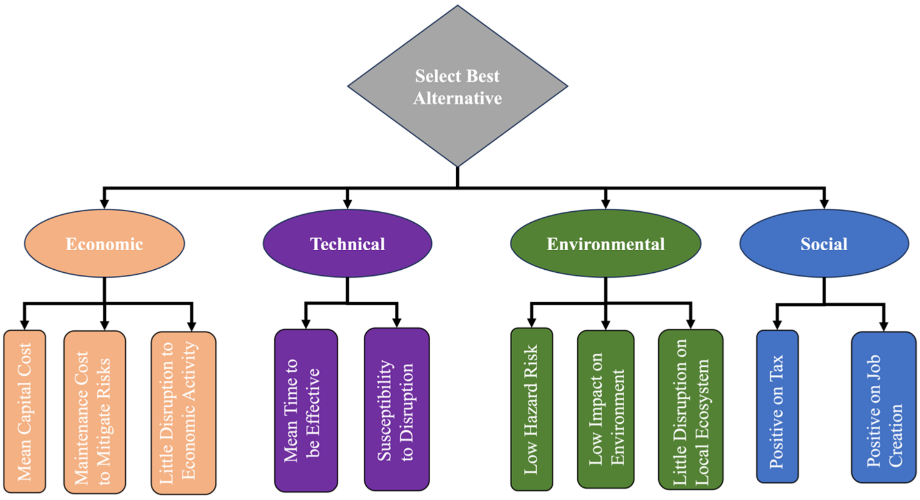


Figure 7. Objective and criteria used for the assessment of alternatives to relieve future water stresses in the MCDA.

Table 4. Estimated costs associated with selected risk-mitigation decision alternatives.

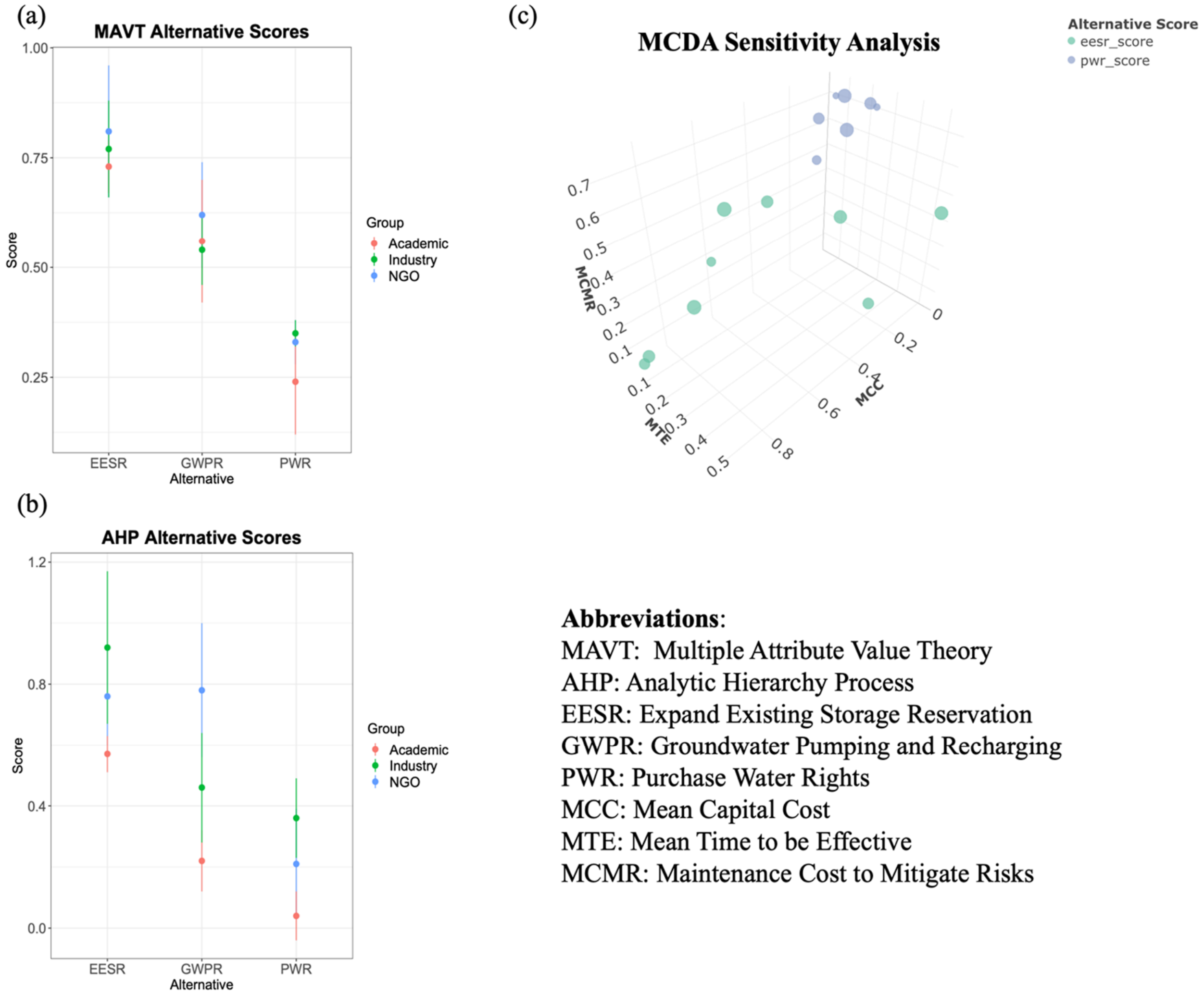
Alternative	Risks	Mean Capital Cost per Acre-Foot (AF)	High Negative Water Gap *	Medium Negative Water Gap *	Low Negative Water Gap *	Cost Range
Purchase Water Rights	Junior rights; competing agricultural needs; timing of availability; susceptibility to disruption	\$7417 **	8943 AF	5366 AF	2683 AF	\$20–66 M
Ground Water Pumping and Recharge	Efficacy and cost of recharge; impacts to human health; susceptibility to disruption	\$3795 **	8943 AF	5366 AF	2683 AF	\$10–34 M
Expand Existing Storage Reservoirs	Need for infrastructure; impacts to environment; susceptibility to disruption	\$2200 **	8943 AF	5366 AF	2683 AF	\$5–19 M

Note(s): * Based on negative water supply gaps calculated in event tree. ** Mean cost per acre-foot (AF) for purchase of water rights [27]. Mean cost per AF for both ground water with recharge and reservoir expansion [28].

Table 5. Criteria valuation ranges and their corresponding ranking.

Mean Capital Cost (USD Million)	Rank
5–20	1
21–35	2
36–50	3
51–65	4
66–80	5
Mean Time to be Effective (Years)	**Rank**
0–5	1
6–10	2
11–15	3
16–20	4
21–25	5
Maintenance Cost to Mitigate Risks (USD Million)	**Rank**
0–5	1
6–10	2
11–15	3
16–20	4
21–25	5
Susceptibility to Disruption (%)	**Rank**
0–20	1
21–40	2
41–60	3
61–80	4
81–100	5

Figure 8 reveals the decision alternative scores based on the two approaches as well as sensitivity analysis results based on the MAVT method. Figure 8a exhibits MAVT alternative scores across three groups: academia, industry, and NGOs. The circle dot represents the mean value of MAVT scores of each decision alternative across all three groups. Additionally, the vertical variation line indicates the uncertainties caused by criterion weighting variations within each group. From Figure 8a, the decision to expand the existing storage reservation has the highest scores, the decision to pump groundwater and recharge it has the middle scores, and the decision to purchase water rights has the lowest scores. In terms of score distribution within each alternative decision, NGOs produced the highest scores in the decision to expand existing storage reservations, and the industry sector had the highest scores in the decision to purchase water rights.



Abbreviations:
MAVT: Multiple Attribute Value Theory
AHP: Analytic Hierarchy Process
EESR: Expand Existing Storage Reservation
GWPR: Groundwater Pumping and Recharging
PWR: Purchase Water Rights
MCC: Mean Capital Cost
MTE: Mean Time to be Effective
MCMR: Maintenance Cost to Mitigate Risks

Figure 8. Alternative scores and MCDA sensitivity analysis results: (**a**) MAVT alternative scores; (**b**) AHP alternative scores; (**c**) MCDA sensitivity analysis on the MACT method.

The decision alternative scores of AHP across the three groups are summarized in Figure 8b. Detailed input information regarding the judgement matrices and consistency ratios are reported in the Supplementary Materials. Specifically, around 65% of experts in academia, 66% of experts in NGOs, and 40% of experts in the industry sector reported to prefer the same optimal decision. Like MAVT scores, the decision to expand existing storage reservations obtained the highest scores, while the decision to purchase water rights obtained the lowest scores. Nonetheless, we identify more considerable uncertainties of scores within each group for each decision (Figure 8b). In addition, the industry group produced the highest score for the decision to expand existing storage reservations instead of the NGO sector compared to the MAVT scores. Additionally, the academic group assigned the lowest AHP scores for all those alternatives compared to the other groups (Figure 8b). Based on the alternative scores from both the MAVT and AHP methods, we can conclude that the decision to expand the existing storage reservation is the most preferred decision across the three groups.

A sensitivity analysis was conducted on the MAVT scores, and the results are shown in Figure 8c. To better visualize the relationship between the MAVT scores and the criteria weighting space, we only consider three criteria here. In Figure 8c, the three independent variables are the three criteria selected here, including mean capital cost, mean time to be effective, and maintenance cost to mitigate risks. From Figure 8c, the different colors of dots indicate the best decision selected based on the MAVT scores evaluated at those different criteria weighting positions. The size of the dots indicates the value of calculated MAVT decision scores. For the sake of simplification, only 16 weighting scenarios were selected to show in this figure. Specifically, these 16 weighting scenarios were also evaluated by the experts. Although we only show those decision selection results at 16 specific criteria weighting positions, a clear discrepancy can be identified: the alternative scores can change according to different positions in the criteria weighting space. In Figure 8a, b, although the experts form academia, industry, and NGOs must judge the criterion differently based on their own knowledge, experience, and interests, the expanding existing storage reservation and groundwater pumping and recharging were found to be more favorable than purchasing water rights based on the alternative scores. This highlights the importance of conducting an MCDA; it can incorporate multiple views of criterion into the decision modeling and analysis process. Nonetheless, Figure 8c indicates that expanding existing storage reservation and purchasing water rights are generally superior to groundwater pumping and recharging at those weighting scheme positions where maintenance cost criterion is assigned a high weight and the mean time to be effective criterion is assigned a low weight. Consequently, this shows that the best decision can certainly vary based on different criteria weighting schemes. In Figure 8a, b, expanding existing storage reservation and groundwater pumping and recharging are the best decisions evaluated by experts across the three groups based on their own interests; however, Figure 8c clearly exhibits that this could certainly change based on different criteria weighting schemes among stakeholders from different perspectives. For example, governmental authorities may value effective use of time over conserving capital costs. Thus, Figure 8 highlights the importance of assessing the best decision under the correct decision problem context; different decision makers can perceive the same alternative from significantly different perspectives.

4. Conclusions and Future Direction

In this study, we assessed an uncertainty-analysis-incorporated risk and decision evaluation framework to alleviate future water stresses in the DCMA. The recent literature that is specific to the DCMA has confirmed the importance of developing a better water management strategy in helping the region sustain a better water security system in the future. Based on the three risk factors considered in this study, we conclude that temperatures are continuously increasing, populations are going to continue growing, and the natural water supply–demand gap is going to shrink. The results of the risk analysis show that the probability that the DCMA will suffer from water scarcity is over 70%, when compared to the current situation. Unlike temperature, the CMIP6 GCM-RCM model simulation predicts that precipitation is not expected to increase over time within the Denver Metro geographic area. While there may be seasonal shifts in precipitation and snowmelt, the total amount of precipitation is not expected to change. It is more likely that future climate scenarios will include hot–dry conditions than hot–wet conditions.

We also illustrated the importance of considering criterion weighing among different stakeholders in decision-making processes when evaluating the potential best alternatives. Given the decision alternatives considered in this study, all options are expensive in terms of monetary costs. Generally, if minimizing mean cost per acre-foot is a primary objective in the decision-making process, the preferred alternatives always tend to avoid the most expensive option, such as directly purchasing water rights. Similarly, if minimizing maintenance cost is a primary objective in the decision-making process, then preferred alternatives tend to avoid the most expensive maintenance cost, such as expanding water storage reservation. The sensitivity analysis elaborated in this study has successfully highlighted this point, and decision makers will be able to easily understand the reason for preferring one decision alternative over the other.

A previous study by Yates et al. [29] illustrated that only drought management would provide a small storage benefit in offsetting the impacts of a shift to a warmer and drier future climate coupled with related environmental changes; thus, engaging water managers in the development of credible and computationally efficient decision support tools is critical in the effort to tackle climate risk management problems. Our study highlights the importance of incorporating a risk analysis framework and proposes several potential decisions to tackle these challenges, e.g., expanding existing water storage reservation and purchasing water rights. However, the decision analysis part also elaborated that none of these decisions may perfectly satisfy all stakeholder interests; this is because they will inevitably have different criterion preferences. Thus, based on the modeling information from this case study, we recommend that local governmental authorities take action in the following aspects to help alleviate future water stresses in the DCMA:

(1) Control the population in the region—it is reasonable to anticipate that a smaller population will reduce the water usage stress in the DCMA. The risk analysis in this case study shows that population growth remains the second most severe risk factor among the risks considered here.

(2) Partner with other local governments to deal with the climate change issue—our case study reveals that climate change is the most significant risk to future water stresses in the DCMA; it is likely to affect many aspects of our society, including agricultural irritation and industrial water usage. However, cooperation with other local authorities to come up with custom policies that can tackle climate change may become critical in addressing this challenge.

(3) Increase the efficiencies of capital investments—our case studies clearly show that criterion weighting associated with capital costs significantly affects the decision evaluation process. Increasing the efficiencies of capital investments can potentially increase the effectiveness of many decision alternatives. We propose that improvements in the efficiencies of capital investments can be achieved through two pathways: technological advancement; political convenience.

(4) Incorporate substantial perceptions from more stakeholders from different sectors of society when making decisions—our case study demonstrates how the decision-making process can be affected by different criterion weighing schemes because stakeholders have different perspectives of interests. Thus, making every effort to consider opinions from as many groups as possible is vital in ensuring the validity of a decision in delivering positive results to every group in the region.

In conclusion, the developed risk and decision analysis in this study highlights the effectiveness of thorough data collection, climate modeling, and consultation with experts in better understanding the risk factors that are present in devising an urban integrated water management strategy. Although decision analysis modeling can be performed through a specific approach, stakeholders' preferences, modeling simulation and data, experts' knowledge, and sensitivity analysis can certainly help ensure that more robust results will be obtained. The developed risk and decision analysis framework presented in this study can quickly gather information resources from experts, climate model simulations, and data from other studies to assist the formation of science-based decisions associated with alleviating future water stresses; however, we acknowledge that the case study elaborated here significantly simplifies the real-world decision-making context. The case study presented here only considers very limited risk factors from limited perspectives. For example, studies have found that social and political elements may have significant influence on the water management decision-making processes carried out by the authorities [30]. Nonetheless, we did not consider these risk factors in our proposed framework for the sake of simplicity. We believe this is the most critical limitation of the case study presented in this paper. Additionally, we want to acknowledge that the overarching goal of this study is to present a risk and decision analysis framework to emphasize the importance of incorporating risk analysis and decision support thinking in the decision-making process. Thus, some of the probability calculations may have been oversimplified in an effort to perfectly model the real-world situation; however, further complication can certainly be adopted through the use of other approaches, such as Bayesian modelling, in the MCDA computation. Moreover, the efficiency and validity of this proposed decision analysis framework cannot be sufficiently tested because it involves many subjective judgments from individual persons. Future research can work towards building a solid database to ensemble extensive model simulations and more expert knowledge to improve the quality of data and the comprehensiveness of the consulting process. Additionally, incorporating more risk factors from more aspects and stakeholders, such as politician's knowledge and opinions, into the current risk and decision analyses framework is expected to enrich the current framework's validity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15224020/s1, Table S1: Summary of experts committee; Table S2: Summary of questionnaire regarding the cumulative probability of each risk factor; Table S3: CMIP6 GCM-RCM climate models analyzed in this study; Table S4: Judgement matrix associated with AHP process; Table S5: Municipal plan comparison.

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References

1. Maddocks, A.; Reig, P. World's 18 Most Water-Stressed Rivers. Available online: https://www.wri.org/insights/worlds-18-most-water-stressed-rivers (accessed on 1 October 2023).
2. Hernández-Cruz, A.; Sandoval-Solís, S.; Mendoza-Espinosa, L.G.; Ramírez-Hernández, J.; Medellín-Azuara, J.; Daesslé, L.W. Assessing Water Management Strategies under Water Scarcity in the Mexican Portion of the Colorado River Basin. *J. Water Resour. Plan. Manag.* **2023**, *149*, 04023042. [CrossRef]
3. Nations Unies. *World Water Assessment Programme*; The United Nations World Water Development Report 2018; United Nations Educational, Scientific and Cultural Organization: New York, NY, USA, 2018; Available online: www.unwater.org/publications/world-water-development-report-2018/ (accessed on 12 November 2023).
4. Boretti, A.; Rosa, L. Reassessing the projections of the world water development report. *NPJ Clean Water* **2019**, *2*, 15. [CrossRef]
5. Richter, B.D. Decoupling urban water use from population growth in the Colorado River basin. *J. Water Resour. Plan. Manag.* **2023**, *149*, 04022082. [CrossRef]

6. Hung, F.; Son, K.; Yang, Y.E. Investigating uncertainties in human adaptation and their impacts on water scarcity in the Colorado river Basin, United States. *J. Hydrol.* **2022**, *612*, 128015. [CrossRef]
7. He, B.; Ding, K.J. Global greenhouse gases emissions effect on extreme events under an uncertain future: A case study in Western Cape, South Africa. *PLOS Clim.* **2023**, *2*, e0000107. [CrossRef]
8. He, B. Efficient Computational Evaluation Tools to Accelerate the Planning of Vulnerability, Resilience, and Sustainability of the Social-Environmental Systems in the City of Nashville. Ph.D. Dissertation, Vanderbilt University, Nashville, TN, USA, May 2023.
9. He, B.; Gilligan, J.M.; Camp, J.V. An index of social fabric for assessing community vulnerability to natural hazards: Model development and analysis of uncertainty and sensitivity. *Int. J. Disaster Risk Reduct.* **2023**, 103913. [CrossRef]
10. Rossi, G.; Peres, D.J. Climatic and other global changes as current Challenges in improving Water Systems Management: Lessons from the case of Italy. *Water Resour. Manag.* **2023**, *37*, 2387–2402. [CrossRef]
11. Christensen, N.S.; Wood, A.W.; Voisin, N.; Lettenmaier, D.P.; Palmer, R.N. The effects of climate change on the hydrology and water resources of the Colorado River basin. *Clim. Change* **2004**, *62*, 337–363. [CrossRef]
12. Peters, C.N.; Baroud, H.; Hornberger, G.M. Multicriteria decision analysis of drinking water source selection in southwestern Bangladesh. *J. Water Resour. Plan. Manag.* **2019**, *145*, 05019004. [CrossRef]
13. Bognár, F.; Benedek, P. A novel AHP-PRISM risk assessment method—An empirical case study in a nuclear power plant. *Sustainability* **2022**, *14*, 11023. [CrossRef]
14. Zhang, F.; Wang, P.; Mu, P.; Wang, M.; Han, L.; Sun, J. A comprehensive evaluation method for the service status of groins in waterways based on an AHP-improved CRITIC combination weighting optimization model. *Sustainability* **2022**, *14*, 10709. [CrossRef]
15. He, B.; Guan, Q. A Risk and Decision Analysis Framework to Evaluate Future $PM_{2.5}$ Risk: A Case Study in Los Angeles-Long Beach Metro Area. *Int. J. Environ. Res. Public Health* **2021**, *18*, 4905. [CrossRef] [PubMed]
16. Lai, Olivia. The Looming Colorado Water Shortage Crisis. Climate Change, Policy & Economics at Earth.org. Available online: https://earth.org/colorado-water-shortage/ (accessed on 1 October 2023).
17. Sullivan, A.; White, D.D.; Larson, K.L.; Wutich, A. Towards water sensitive cities in the Colorado River Basin: A comparative historical analysis to inform future urban water sustainability transitions. *Sustainability* **2017**, *9*, 761. [CrossRef]
18. Star, Indianapolis. Denver-Aurora-Lakewood, CO Metro Area Demographics and Housing 2020 Decennial Census. Indianapolis Star. Available online: https://data.indystar.com/census/total-population/total-population-change/denver-aurora-lakewood-co-metro-area/320-19740/ (accessed on 1 October 2023).
19. Aurora Water. Municipal Water Efficiency Plan Aurora Water City of Aurora, Colorado. Aurora Water. Available online: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://cdnsm5-hosted.civiclive.com/UserFiles/Servers/Server_1881137/File/Residents/Water/Water%20System/Aurora%20Water%20Facts/Final_2015_ConservationPlan_update_3.18.16.pdf (accessed on 1 November 2023).
20. Douglas County. Available online: http://www.douglas.co.us/water/water-supply/ (accessed on 12 November 2023).
21. Colorado Water Plan. Available online: https://www.colorado.gov/pacific/cowaterplan/colorados-water-plan-final-2015 (accessed on 14 November 2023).
22. WISE Agreement. WISE Partnership-Water Delivery Agreement between Denver Water, the City of Aurora, Acting by and through its Utility Enterprise, and the South Metro Water Supply Authority. City of Aurora, Colorado. Available online: https://www.sec.gov/Archives/edgar/data/276720/000110262415000024/exh10_3.htm (accessed on 1 November 2023).
23. Angelis, A.; Kanavos, P. Multiple criteria decision analysis (MCDA) for evaluating new medicines in health technology assessment and beyond: The advance value framework. *Soc. Sci. Med.* **2017**, *188*, 137–156. [CrossRef] [PubMed]
24. Saaty, T.L. *Multicriteria Decision Making: The Analytic Hierarchy Process*; RWS Publications: Pittsburgh, PA, USA, 1992.
25. Saaty, T.L. Decision making with the analytic hierarchy process. *Int. J. Serv. Sci.* **2008**, *1*, 83–98. [CrossRef]
26. Macrotrends. Denver Metro Area Population 1950–2023. Available online: https://www.macrotrends.net/cities/22972/denver/population#:~:text=The%20current%20metro%20area%20population,a%201.22%25%20increase%20from%202021 (accessed on 1 October 2023).
27. Payne, T.; Smith, M.; Landry, C. Price Determination and Efficiency in the Market for South Platte Basin Ditch Company Shares. *J. Am. Water Resour. Assoc.* **2014**, *50*, 1488–1500. [CrossRef]
28. Choy, I.; McGhee, G.; Rohde, M. Recharge: Groundwater's Second Act. Water in the West. Stanford Woods Institute for the Environment. Available online: http://waterinthewest.stanford.edu/groundwater/recharge/ (accessed on 16 October 2023).
29. Yates, D.N.; Miller, K.A.; Wilby, R.L.; Kaatz, L. Decision-centric adaptation appraisal for water management across Colorado's continental divide. *Clim. Risk Manag.* **2015**, *10*, 35–50. [CrossRef]
30. Cosgrove, W.J.; Loucks, D.P. Water management: Current and future challenges and research directions. *Water Resour. Res.* **2015**, *51*, 4823–4839. [CrossRef]