Supporting Material for "Evaluation of Future Integrated Urban Water Management using Risk and Decision Analysis Framework: A Case Study in Denver-Colorado Metro Area (DCMA)"

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Acknowledgement

Introduction

This study proposes a valuable risk and decision analysis framework for analyzing the future water stresses caused by three risk factors: population growth, climate change, and the water supply-demand relationship. In this supplementary material, we provide additional information regarding the expert's opinion consultation process. Specifically, we formed a committee of experts consisting of a total of 30 people who have expertise in the demographic census, economic analysis and prediction, water resources analysis and prediction, and climate change area, respectively.

Table S1 summarizes the information associated with the experts' committee in this study. Specifically, for the demographic census area of expertise, we consulted nine experts, with five experts coming from the academic area, three experts coming from NGO institutions, and one expert coming from the industry sector. For the economic assessment area, we consulted a total of seven experts, with one from the academic area, one from an NGO institution, and five experts coming from the industry sector. For the climate change area, six experts were consulted, which all come from academic institutions. Finally, for the water resources evaluation area, we consulted eight experts, of which four experts came from the industry sector, two came from the academic sector, and two came from Non-Governmental Organization (NGO) institutions.

Table S1. Summary of experts committee.

Area of Expertise	Number of Experts	Sector
Demographic Census	9	Academic (5), NGO (3), Industry (1)
Economic Analysis	7	Academic (1), NGO (1), Industry (5)
Climate Change	6	Academic (6)
Water Resources Analysis	8	Industry (4), Academic (2), NGO (2)

To obtain the approximated cumulative probabilities for the three risk factors associated with future water stresses in the Denver-Colorado Metro Area (DCMA), we created a questionnaire separately for each risk factor as a survey. Then, answers and responses for these questionnaires from each and every expert were collected. The questionnaire for experts for each risk factor is summarized in Table S2.

Table S2. Summary of questionnaire regarding the cumulative probability of each risk factor.

Risk Factor	Question
Population Expansion	(1) In your opinion, what is the largest possible population increase rate in the DCMA within the future 20 years?
	(2) In your opinion, what is the probability that the population increase rate in the DCMA will be less than the 75th percentile of the largest possible population increase rate based on your answer to the question (1)?
	(3) In your opinion, what is the probability that the population increase rate in the DCMA will be less than the 50th percentile of the largest possible population increase rate based on your answer to the question (1)?
	(4) In your opinion, what is the probability that the population increase rate in the DCMA will be less than the 25th percentile of the largest possible population increase rate based on your answer to the question (1)?
	(5) In your opinion, what is the range of the population increase rate that you would consider as a high increase scenario?
	(6) In your opinion, what is the range of the population increase rate that you would consider as a medium increase scenario?
	(7) In your opinion, what is the range of the population increase rate that you would consider as a low increase scenario?
Temperature Increase	(1) In your opinion, what is the largest possible temperature increase rate in the DCMA within the future 20 years?
	(2) In your opinion, what is the probability that the temperature increase rate in the DCMA will be less than the 75th percentile of the largest possible temperature increase rate based on your answer to the question (1)?
	(3) In your opinion, what is the probability that the temperature increase rate in the DCMA will be less than the 50th percentile of the largest possible temperature increase rate based on your answer to the question (1)?
	(4) In your opinion, what is the probability that the temperature increase rate in the DCMA will be less than the 25th percentile of the largest possible temperature increase rate based on your answer to the question (1)?

	(5) In your opinion, what is the range of the temperature increase rate that you would consider as a high increase scenario?
	(6) In your opinion, what is the range of the temperature increase rate that you would consider as a medium increase scenario?
	(7) In your opinion, what is the range of the population increase rate that you would consider as a low increase scenario?
Water Supply and Demand Relationship	(1) In your opinion, what is the largest possible water supply demand gap in the DCMA within the future 20 years?
	(2) In your opinion, what is the probability that the water supply and demand gap in the DCMA will be less than the 75th percentile of the largest possible water supply and demand gap based on your answer to the question (1)?
	(3) In your opinion, what is the probability that the water supply and demand gap in the DCMA will be less than the 50th percentile of the largest possible water supply and demand gap based on your answer to the question (1)?
	(4) In your opinion, what is the probability that the water supply and demand gap in DCMA will be less than the 25th percentile of the largest possible water supply and demand gap based on your answer to the question (1)?
	(5) In your opinion, what is the range of the water supply and demand gap that you would consider as a high increase scenario?
	(6) In your opinion, what is the range of the water supply and demand gap that you would consider as a medium increase scenario?
	(7) In your opinion, what is the range of the water supply and demand gap that you would consider as a low increase scenario?

To further evaluate the regional climate change prediction, a total of 8 global climate model – regional climate model (GCM-RCM) from Department of Energy (DoE) CMIP6 were incorporated in this study. These models' data facilitate the judgment of our experts' opinions on future climate change predictions. Table S3 summarizes the models analyzed in this study.

Table S3. CMIP6 GCM-RCM climate models analyzed in this study.

Model	Time Frequency	Variable	Experiment
ACCESS-ESM1-5	Monthly, yearly	Tasmax, prcp	Rcp45, Rcp85
AWI-CM-1-1-MR	Monthly	Tasmax, prcp	Rcp45, Rcp85
BCC-CSM2-MR	Monthly	Tasmax, prcp	Rcp45, Rcp85
CESM1-WACCM-SC	Monthly, yearly	Tasmax, prcp	Rcp45
CESM2	Monthly	Tasmax, prcp	Rcp45
CMCC-CM2-SR5	Monthly, yearly	Tasmax, prcp	Rcp45, Rcp85
CNRM-CM6-1	Monthly	Tasmax, prcp	Rcp45
HadGEM3-GC31-MM	Monthly, yearly	Tasmax, prcp	Rcp85

For the AHP analysis, the standard judgment 9-point scores of Saaty's [24] work were adopted. The AHP judgement matrix was summarized in the following Table S4, and the consistency ratio was calculated as 0.068.

Table S4. Judgement matrix associated with AHP process.

Criteria	Mean Capital Cost	Mean Time to be Effective	Maintenance Cost to Mitigate Risks	Priority
Mean Capital Cost	1	5	7	0.73
Mean Time to be Effective	1/5	1	3	0.19
Maintenance Cost to Mitigate Risks	1/7	1/3	1	0.08

The State's recent Water Plan [19] includes climate scenarios and possible impacts on water supply and demand but falls short of specific quantitative analysis of impacts below the

state level [21]. None of the municipal plans surveyed for this assessment adequately addressed population growth and climate scenarios when considering future water supply and demand and the potential for negative water supply gaps. The following plans shown in Table S4 recognize drought as a relatively significant risk and consider population and climate to varying degrees in their consideration of drought.

Table S5. Municipal plan comparison.

Document	Drought Likelihood	Drought Severity	Drought Risk	Population Increase Considered	Climate Change Considered
Denver Regional (includes Adams, Arapahoe, Denver, and Douglas) Natural Hazard Mitigation Plan 2010 Update	High	Significant	High	Yes	No mention
City and County of Denver Hazard Identification and Risk Assessment October 2011	High	Moderate	Moderate	Yes	Reference only
Douglas County Local Hazard Mitigation Plan 2015	Moderate	Moderate	Moderate	Yes	No mention

Document	Addresses Water and Future Development	Discusses Drought	Population Increase Considered	Climate Change Considered
Douglas County Comprehensive Master Plan 2014	Identifies future water resources as critical to continued development	Yes	Yes	Not mentioned

Aurora Comprehensive Plan 2009	Identifies future water resources as critical to continued development	Yes	Yes	Discussed, but not clearly incorporated

Each plan clearly identifies concerns associated with future drought and water supply issues. Some discuss possible implications of climate change but do not integrate any findings or data into future risk assessment. The plans focus primarily on changes in population, stating that the fastest-growing counties are most vulnerable to drought impacts and that, in general, counties experiencing higher growth are also likely to experience increased competition over existing water supplies. Of all assessed plans, Aurora addresses the issues of drought, water supply, and water demand in the most comprehensive way. Aurora's comprehensive plan asserts that it has included climate impacts in future projections, but it is not apparent how or to what extent this was done. In general, plans are consistent in saying that water providers will be better insulated from drought impacts if they have senior water rights if they actively plan and are prepared for drought, and if they have a diverse water supply portfolio.

Despite recent drought impacts, most plans consider widespread drought as uncommon due to reliance on historical drought events to project future occurrences. While jurisdictions recognize drought and water scarcity as part of the overall fabric of the state, there may be chronic underrepresentation of drought vulnerability and impacts due to failure to sufficiently incorporate climate impacts into drought risk assessment. Efforts undertaken in the recent 2015 Colorado Water Plan may help to direct municipalities toward greater incorporation of climate scenarios in county and city-specific planning efforts, but that remains to be seen.

Acknowledgment

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