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Los Angeles

Health Impacts of Expanding Urban Recycled Water Use in California

A dissertation submitted in partial satisfaction of the

requirements for the degree Doctor of Philosophy

in Environmental Health Sciences

by

Sharona Yael Sokolow

2017

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ABSTRACT OF THE DISSERTATION

Health Impacts of Expanding Urban Recycled Water Use in California

by

Sharona Yael Sokolow

Doctor of Philosophy in Environmental Health Sciences

University of California, Los Angeles, 2017

Professor Hilary Godwin, Chair

The overarching goal of the work described herein is to elucidate how expanding recycled water systems throughout California would impact human health and how we might lower barriers to the expanded use of recycled water in this region. We focused on three topics: (1) comparing the health impacts of expanded use of recycled water to other water conservation strategies in Southern California; (2) conducting a detailed case study on the financial costs, greenhouse gas emissions, energy and health of different water source scenarios for Long Beach Water District (LBWD); and (3) interviewing public health and water industry professionals to understand barriers to expanded use of recycled water in California. Based on our first study, we concluded that expansion of recycled water has the potential to yield greater net health benefits than other water conservation strategies in Southern California, when the full range of health impacts of water conservation strategies, including those related to energy use and human health, are taken

into consideration. In our second study, we found that maximizing recycled water use in LBWD would lower energy and greenhouse gas emissions and be more cost effective than other water source options by as early as 2025. In our third study, we found that critical stakeholders perceive that the majority of the barriers that prevent expansion of recycled water use in Southern California fall into the following categories: regulatory restrictions, infrastructure costs, lack of funding, requirements for new technology, adverse health effects, and negative public perception of recycled water. Taken together, these studies provide clear insights into the advantages associated with expanding use of recycled water in Southern California, the gaps between perceived and real barriers to expanded use of recycled water, and how committed stakeholders—including those in the public health profession—can help ensure that water solutions that benefit our region's health are pursued going forward.

The dissertation of Sharona Yael Sokolow is approved.

Yoram Cohen

Richard Jackson

Yifang Zhu

Hilary Godwin, Committee Chair

University of California, Los Angeles, 2017

TABLE OF CONTENTS

ABSTRACT OF THE DISSERTATION ii

LIST OF FIGURES AND TABLES iv

ABBREVIATIONS USED HEREIN v

ACKNOWLEDGEMENTS vi

VITA xiv

CHAPTER 1: Introduction and Overview of the Organization of the Thesis 1
REFERENCES FOR CHAPTER 1 9

CHAPTER 2: Impacts of Urban Water Conservation Strategies on Energy, Greenhouse Gas Emissions and Health: Southern California as a Case Study 14
ABSTRACT 14
INTRODUCTION 15
How California's current use of water impacts energy, GHG emissions, and health. 17
METHODS 20
Identifying connections among water, energy, GHG emissions, and health. 20
Technical Advisory Committee. 20
Assessing energy demand. 21
Data analysis. 21
FINDINGS 23
Health impacts of landscape irrigation bans. 23
Health impacts of expanding use of alternative water sources. 25
DISCUSSION AND IMPLICATIONS 27
Lowering public perception barriers to expanded recycled water use. 29
Lowering regulatory barriers to expanded recycled water use in California. 30
Lowering financial barriers to expanded recycled water use in California. 30
CONCLUSION 31
REFERENCES FOR CHAPTER 2 32

CHAPTER 3: Assessing Health Impacts of Direct Potable Reuse for the Urban Water Supply: Case Study of Long Beach, California. 45
ABSTRACT 45
INTRODUCTION 46
METHODS 49
HIA methodology. 49
Development of the logic framework: literature review and discussions with experts. 50
Case study: Southern California's Long Beach Water District. 51
RESULTS AND DISCUSSION 58

Water source scenarios used to explore impacts of water source choices for Long Beach Water District. 58
Summary of qualitative factors that have impacted water source choices and how they related to water sources in the LBWD case study. 59
Summary of implications of quantitative factors for the water scenarios in the LBWD case study. 64
Downstream health impacts related to water source decisions and the implications for LBWD water source scenarios. 67
LIMITATIONS 73
Limitations in the data available for the LBWD case study and resulting in uncertainty of the calculations for energy demand, GHG emissions, and cost. 74
CONCLUSION 76
REFERENCES FOR CHAPTER 3 79

CHAPTER 4: Perspectives on the Barriers Towards the Future of Recycled Water in California: Results from Interviews with Key Stakeholders 106
ABSTRACT 106
INTRODUCTION 107
METHODS 109
Literature review. 109
Study sample. 110
Interviews and analysis. 111
Analysis 112
RESULTS 112
Regulatory barriers. 113
Technological barriers. 116
Infrastructure barriers. 117
Funding barriers. 118
Public perception. 121
Health risks. 123
DISCUSSION 125
Lessons learned: Importance of public perception barriers to recycled water. 126
Lessons learned: Ways that public health professionals can contribute to lowering barriers to recycled water use. 127
LIMITATIONS 128
CONCLUSIONS 129
REFERENCES FOR CHAPTER 4 131

CHAPTER 5: Overarching Conclusions and Recommendations for Future Studies 138
THEMES AND INSIGHTS 140
Expanded Use of Recycled Water in Southern California Has the Potential to Result in Health Benefits, When Factors Related to the Water-Energy-GHG Nexus Are Considered 140
Public Health Professionals Can Play An Important Role in Promoting the Health-Related Benefits of Recycled Water by Working With Colleagues in Other Sectors to Advance the Safe and Appropriate Expansion of Recycled Water Use 143

Lessons Learned from this Work Regarding Recycled Water and its Barriers to Expansion in Southern California Have Broader Implications..... 144
REFERENCES FOR CHAPTER 5 145

APPENDIX 1: Supporting Information for Chapter 3 147
SUPPLEMENTAL METHODS 148
Calculation of potential supply of wastewater available for reclamation and treatment for either DPR in LBWD. 148
Detailed explanation of source of energy demand numbers provided in Table 3-1 and rationale for selection of these sources. 150
Detailed methods for regression analysis to estimate missing energy demand data. 156
Detailed information about sources of estimate costs for LWBD water sources. 160
REFERENCES FOR APPENDIX 1 167

LIST OF FIGURES AND TABLES

For Chapter 2: (previously published in the *American Journal of Public Health*)

Figure 2-1: Water sources have differing impacts on human health 40

Figure 2-2: Energy intensity of California's water sources 41

Table 2-1: Positive and negative impacts of landscape irrigation bans 43

Table 2-2: Positive and negative health impacts of alternative water sources 44

For Chapter 3:

Figure 3-1: Factors that have traditionally been considered when making water source decisions 92

Figure 3-2: Logic framework of water source decision making and the potential for downstream health-related impacts. 93

Figure 3-3: Projected costs of each water source scenario for LBWD in 2025 and 2035 compared to baseline (2010) 94

Table 3-1: Projected amount of water from each source assumed for each scenario in Long Beach Water District case study developed herein 95

Table 3-2: Estimated current energy demand for components of current and potential water sources used by Long Beach Water District (LBWD) and total estimated energy demand for LBWD water sources. 96

Table 3-3: Estimated energy demand and greenhouse gases emitted for each water source scenario for Long Beach Water District in 2025 and 2035 compared to baseline (2010) 97

Table 3-4: Data sources for each water source for Long Beach Water District case study 99

Table 3-5: Estimated unit price (in dollars per AF) for current and potential water sources Long Beach Water District used in calculations 100

Table 3-6: Low, medium and high cost projections for each Scenario in Long Beach Water District case study for 2025 and 2035 compared to Baseline (2010) 101

Table 3-7: Summary of key differences in the health impacts and other considerations that influence water source selection for Long Beach Water District water source scenarios 102

Table 3-8: Identification of the water source that contributes the most to cost for each scenario in the Long Beach Water District case study in 2025 and 2035 compared to baseline (2010) 104

Table 3-9: Factors driving uncertainty in costs and energy for imported water and seawater desalination at LBWD water 119

For Chapter 4:

Figure 4-1: Comparison of treatment processes required for direct potable reuse (DPR) and indirect potable reuse (IPR) of recycled water 135

Table 4-1: Main interview questions 136

Table 4-2: Barriers identified by different types of stakeholders 137

For Appendix 1:

Table A1-1: Water demand calculations for water source scenarios within Chapter 3 164

Table A1-2: Water demand calculations for water source scenarios within Chapter 3 165

Table A1-3: Table of LBWD system parameters used in forecasts 166

ABBREVIATIONS USED HEREIN

ADHD	Attention Deficit Hyperactivity Disorder
AF	Acre-Foot/Acre-Feet
AOP	Advanced Oxidation Process
AWT	Advanced Water Treatment
AwwaRF	American Water Works Association Research Foundation
DPR	Direct Potable Reuse
GHG	Greenhouse Gas
HIA	Health Impact Assessment
IPR	Indirect Potable Reuse
kWh	Kilowatt Hour
LASD	Los Angeles Sanitation District
LBWD	Long Beach Water District
LCWRP	Los Coyotes Water Reclamation Plant
MCL	Maximum Contaminant Level
MWD	Metropolitan Water District (Southern California)
NGO	Non-governmental Organization
OCWD	Orange County Water District
SB	Senate Bill (California)
SCE	Southern California Edison
SDCWA	San Diego County Water Authority
SWRCB	State Water Resources Control Board (California)
TAC	Technical Advisory Committee

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of Public Health's Health Impact Assessment Project in collaboration with The Los Angeles County Department of Public Health. Available at http://www.ph.ucla.edu/hs/health-impact/reports.htm

Sokolow, S., Godwin, H., Cole, B. L. (2016) *Impacts of Urban Water Conservation Strategies on Energy, Greenhouse Gas Emissions, and Health: Southern California as a Case Study.* American Journal of Public Health: May 2016, Vol. 106, No. 5, pp. 941-948.

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CHAPTER 1

Introduction and Overview of the Organization of the Thesis

California is currently facing its most severe drought of the past 50 years and is projected to experience increasingly severe and frequent droughts in the future as a result of climate change.[1-5] The same trends are expected for the American Southwest as whole, including regions that currently supply Southern California with the majority of its water.[1] As a result, Southern California's current reliance on imported water is not sustainable, and a top priority is to identify more sustainable approaches to supplying water for California and its growing population.[6]

The need to increase the safety and reliability of the water supply is not exclusively a California issue, but rather a global problem. Water is essential for maintaining the health of the population, through needs such as personal hygiene and maintenance of agricultural production. A safe water supply is not accessible for millions of people across the world. Estimates suggest that 750 million people worldwide[7] (1 in 9 people) do not have access to safe and clean drinking water — a number expected to increase with the onset of climate change, rising greenhouse gas (GHG) concentrations, and increasing populations.[8] In California, some of the most significant projected impacts of climate change on health include: (1) increased incidence of temperature-related illness and death, more air-pollution-related illness and death; (2) increased morbidity and mortality associated with sea level rise and wildfires; and (3) food and water shortages related to increasing temperatures, changes in precipitation patterns, and increased frequency of extreme weather events.[2]

Since 2009, California's legislature has made several advances toward protecting the state's water supply and promoting water conservation. In 2009, California's legislature passed the largest-to-date water legislation package in state history, which included Senate Bill x7-7 (SBx7-7). SBx7-7, a key component of the legislation, mandated a 20% reduction of urban water use in all water districts across the state by the year 2020.[9,10] In 2014, to deal with California's prolonged drought, voters approved an even larger water legislation package, Proposition 1. Proposition 1 includes a one billion dollar bond to support California's water needs, including $725 million for recycled water projects.[11] Most recently, in the spring of 2015, California Governor Jerry Brown called upon urban water suppliers to cut water use by 25% from baseline 2013 usage levels.[12]

In addition to policies to promote sustainability of water sources and conservation, researchers have determined that one method to improve the sustainability of California's water supply is through expanding use of recycled water, both for potable and non-potable uses.[13-16] Integrating recycled water treated for potable reuse into supply systems can help boost drinking water supplies from local sources that otherwise rely on energy-intensive imported water or groundwater.[5] Recycled water treated for non-potable reuse, such as landscape irrigation, can indirectly benefit supplies of drinking water by decreasing the amount of high quality potable water used for landscape irrigation and other applications that do not involve direct human contact.[14] In urban settings, expanded use of recycled water has great potential to reduce the need for costly, energy-intensive imported water.[3,5,17] Across the world, use of recycled water for both

potable and non-potable purposes has been successful in improving water sustainability within water scarce regions.[13-16,18]

One barrier to implementing recycled water specifically for potable uses is the fear that the water is unclean, or that it may cause disease.[19-23] In general, research suggests that health risks associated with recycled water are minimal.[18,24,25] Toxicological health risk assessments conducted for potable reuse projects in Tampa[24] and Denver[25] exposed rats and mice to varying concentrations of recycled water treated for potable reuse; these studies did not demonstrate any reproductive, developmental, or chronic toxicity from consuming recycled water treated for potable reuse. Additional toxicological studies conducted by the National Research Council evaluated long term toxicity exposure assessments of 150x and 500x recycled water concentrations in fish over multiple generations, implemented in Singapore and Orange County; these studies found no statistically significant differences in morphology, reproduction, or gender ratios in offspring or mortality. Over multiple generations, exposure to the recycled water concentrates did not cause estrogenic or carcinogenic effects within the fish.[26] A study by the National Research Council used quantitative comparative risk assessment to determine potential risk associated with specific contaminants that may be present in recycled water treated for potable reuse, including pharmaceuticals, personal care products, and classes of contaminants including nitrosamines, disinfection byproducts (DBPs), hormones, pharmaceuticals, antimicrobials, hormones, flame retardants, and perfluorochemicals. These results were compared to those obtained for water from conventional drinking water plants originating from three places: (1) surface water; (2) groundwater; and (3) water treated by microfiltration, reverse osmosis and advanced oxidation.[18,27-31] Contaminant levels were measured within each water

supply sample and compared with each other. These assessments suggest that the levels of contaminants in recycled water that has been treated by microfiltration, reverse osmosis, and advanced oxidation do not exceed levels in existing fresh potable water supplies.[18,31]As a result, these and other authors have estimated that expanded use of recycled water that is treated for potable reuse would contribute relatively little to the total United States disease burden[18,32] Maintaining low risk associated with recycled water for potable reuse requires strict adherence to treatment standards for recycled water; water that is not treated to the appropriate level can pose health risks.[33,34] Some constituents, such as microbial pathogens and trace organic chemicals, have the potential to affect human health, depending on their concentration and routes of exposure.[32,33] Pathogens are of particular concern because of their acute human health effects; viruses require special attention because of their low infectious dose and small size.[14,33,35,36] Furthermore, because recycled water is utilized for many potential applications, the contaminants of concern depend on the end use.[14,33,35-37] For example, contaminants in treated water that may have health effects may not be problematic in industrial or irrigation applications where human exposure is limited.[14,33,35,37] All told, however, prior studies suggest that health concerns about recycled water can be addressed with available treatment technologies.[18,32,36]

We chose to focus our research on another environmental health policy issue facing the water and public health communities. With a focus on recycled water, we examine how different water sources are both affected by and affect climate change, and how intermediate factors related to water source choices have the potential to affect health. While it is widely accepted that climate change will affect the quantity and frequency of droughts and floods across the world,[2,8,38] what is less recognized is how changes in water sources and water resources management will be

affected by climate change and how, downstream, these decisions may impact health. To better understand how climate change and water source decisions may impact health, we chose to take a holistic view of factors decision makers may consider. Factors we considered with potential for downstream health impacts include: (1) sustainability, (2) water quality, (3) energy demand and (4) GHG emissions, (5) overall costs, (6) technical feasibility, and (7) public perception of each water source. For example, energy demand can differ considerably among water sources, and decision makers should understand how energy differences have the potential to affect health. One pathway through which energy demand can affect health is during production, where energy produced via coal-fired power plants release GHGs. Increases in energy production result in increases in GHG emissions, which can both contribute to air pollution and exacerbate the effects of climate change through increasing regional temperatures.[2,39] Air pollution may result in health-related impacts through to respiratory disease, and increased regional temperatures may result in health-related impacts through heat stress or heat stroke.[2,39] By focusing our research on a holistic of view water source decision making, we further explored a pathway through which water sources have the potential to impact public health in the future.

In this thesis, we examined the issue of expanding recycled water in Southern California through the lens of a public health professional. In **Chapter 2** of this thesis (previously published in the *American Journal of Public Health*),[17] we specifically explored how the health impacts of expanded use of recycled water in Southern California compare to the health impacts of other effective water conservation strategies. This research originated from a comprehensive health impact assessment (HIA) of different water conservation strategies.[40] We found that energy and costs associated with California's water system have the potential to affect health. Thus, in

Chapter 3, we created a holistic framework for determining the health impacts of water source decisions which included an assessment of energy demand, GHG emissions, costs, water quality, sustainability indicators, technical feasibility, and public perception of different water sources using Long Beach Water District (LBWD) as a case study with relevance to other drought-stricken water districts (**Chapter 3**). Finally, in Chapter 4 we conducted interviews with public health and water industry professionals to elucidate barriers to expanded use of recycled water within California. More detailed summaries of the results presented in each of these chapters are provided subsequently.

Chapter 2: As part of a larger effort funded in part by the Pew Health Impact Project and Robert Wood Johnson Foundation, we previously conducted a comprehensive HIA of urban water conservation methods in compliance with California Senate Bill x7-7.[40] In this HIA, we identified a number of water conservation measures with the greatest potential to impact California's water-energy nexus. In Chapter 2 of this thesis (previously published in the *American Journal of Public Health*[17]), we conduct a more nuanced health impact analysis of several of these conservation measures, including the following: (1) a ban on landscape irrigation, and (2) expanded use of alternative water sources (e.g., desalination or recycled water). The results of the HIA suggest that the expansion of recycled water for non-potable applications has potential to result in a net positive impact on water conservation, energy use and human health. The benefits of expanding recycled water use were also found to exceed those of banning landscape irrigation or maintaining the status quo.

Chapter 3: In this study, we used Southern California's LBWD as a case study to create a holistic framework for assessing potential health-related impacts of water source decision making. Within our framework, factors we assessed include: sustainability, GHG emissions, water quality, energy demand, costs, technical feasibility, and public perception of increasing water reuse relative to other water source alternatives (e.g., imported and/or desalinated water). For a quantitative assessment, we modeled energy demand, GHG emissions, and costs of different water source scenarios for LBWD based on real and projected water demand in 2010, 2025, and 2035. This analysis revealed that increasing recycled water use in LBWD, including recycled water use for potable applications, would reduce the total energy used, GHG emissions, and costs by 2025 compared to Business as Usual. In addition, expanding the use of recycled water has positive health implications for water sustainability considerations and minimal technical or infrastructure updates compared to other new water sources (i.e., desalination). Because energy use and GHG emissions are intricately linked to negative health impacts (**Chapter 2**), we conclude that maximizing recycled water use would result in net benefits to health. To receive these benefits, we recommend that urban water districts should work now to develop the infrastructure required to maximize use of recycled water for potable reuse.

Chapter 4: In this study, we report the results of 12 non-scheduled standardized narrative interviews with stakeholders in the water and public health communities on barriers to expansion of recycled water use in California. Perceived barriers were identified related to limited regulations, infrastructure costs, lack of funding, developing new technology, adverse health effects, and negative public perception of recycled water. Respondents provided concrete

suggestions for how to lower these barriers as well as insights into the roles that public health professionals could play in this effort.

Taken together, these studies provide compelling evidence that expanded use of recycled water in Southern California could result in both health (**Chapter 2**) and economic (**Chapter 3**) benefits, despite the fact that health concerns are frequently perceived as barriers to expansion of recycled water initiatives. This work also provides critical insights into barriers to expansion of recycled water initiatives and ways in which these barriers could be addressed (**Chapter 4**). In **Chapter 5**, I summarize the overarching insights gained from this work, along with priorities for future studies. Supporting information for **Chapters 2** and **3** is provided in **Appendices 1** and **2**, respectively.

REFERENCES FOR CHAPTER 1

1. MacDonald G. Water, climate change, and sustainability in the Southwest. *P Natl Acad Sci USA*. 2010;107(50): 21256–21262.
2. Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. Impact of regional climate change on human health. *Nature.* 2005;438(7066):310-317.
3. Cooley H, Christian-Smith J, Gleick P. *California's Next Million Acre-Feet: Saving Water, Energy and Money.* Oakland, CA: Pacific Institute; 2010.
4. Gleick PH, et al. *Waste Not, Want Not: The Potential for Urban Water Conservation in California.* Pacific Institute; 2003.
5. Wolff GW, Cohen R, Nelson B, Natural Resources Defense Council. Energy down the drain: The hidden costs of California's water supply. https://www.nrdc.org/water/conservation/edrain/edrain.pdf. Published 2004.
6. United States Census Bureau. California Quick Fact. http://quickfacts.census.gov/qfd/states/06000.html. Published 2010.
7. World Health Organization and UNICEF. Progress on drinking water and sanitation 2014 update. http://www.wssinfo.org/fileadmin/user_upload/resources/JMP_report_2014_webEng.pdf Published 2014.
8. Intergovernmental Panel on Climate Change. Climate change 2013: The physical science basis. https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WGIAR5_SPM_brochure_en.pdf. Published 2013.
9. California Department of Water Resources. *20x2020 Water Conservation Plan.* Published 2010.

10. California State Senate. *Senate Bill x7-7: An act to amend and repeal Section 10631.5 of, to add Part 2.55 (commencing with Section 10608) to Division 6 of, and to repeal and add Part 2.8 (commencing with Section 10800) of Division 6 of, the Water Code, relating to water.* November 10, 2009.

11. California State Assembly. *Assembly Bill 1471: The Water Quality, Supply and Infrastructure Improvement Act of 2014 that passed November 4, 2014 general election as Proposition 1;* 2014.

12. California Government Code Executive Order No. B-29-15. 2015.

13. Tchobanoglous G, Cotruvo J, Crook J, et al. *Framework for Direct Potable Reuse.* WateReuse Foundation, American Water Works Association, Water Environment Foundation, National Water Research Institute; 2015.

14. Raucher R, Tchobanoglous G. The opportunities and economics of direct potable reuse. WateReuse Foundation: https://www.watereuse.org/product/14-08-1. Published 2014.

15. Tchobanoglous G, Leverenz H, Nellor M, Crook J. *Direct Potable Reuse: A Path Forward.* WateReuse Research Foundation; 2011.

16. Leverenz H, Tchobanoglous G, Asano T. Direct potable reuse: A future imperative. *J Water Reuse Desal.* 2011;1(1):2-10.

17. Sokolow S, Godwin H, Cole BL. Impacts of urban water conservation strategies on energy, greenhouse gas emissions, and health: Southern California as a case study. *Am J Public Health.* 2016;106(5).

18. National Resources Council of the National Academies. *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater.* 2012.

19. Hurlimann A, Dolnicar S. Public acceptance and perceptions of alternative water sources: A comparative study in nine locations. *Int J Water Resour D.* 2016;32(4):650-673.

20. Hartley T. Public perception and participation in water reuse. *Desalination.* 2005;187(1-3):115-126.

21. Bridgeman J. Public perception towards water recycling in California. *Water Environ J.* 2004;18(3):150-154.

22. Garcia-Cuerva L, Berglund EZ, Binder AR. Public perceptions of water shortages, conservation behaviors and support for water reuse in the United States. *Resour Conserv Recy.* 2016;113:106-115.

23. Ross VL, Fielding KS, Louis WR. Social trust, risk perceptions and public acceptance of recycled water: Testing a social-psychological model. *J Environ Manage.* 2014;137:61-68.

24. CH2M Hill. *Tampa Water Resource Recovery Project Pilot Studies.* Tampa, Florida: CH2M Hill; 1993.

25. Lauer WC, Rogers SE. The Demonstration of Direct Potable Reuse: Denver's Pioneer Project. *American Water Works Association/Water Education Foundation Proceedings.* 1996:269-289.

26. National Resources Council of the National Academies. *Issues in Potable Reuse: The Viability of Augmenting Drinking Water Supplies with Reclaimed Water.* Washington DC National Academies Press 1998.

27. Bull R, Crook J, Whittaker M, Cotruvo J. Therapeutic dose as the point of departure in assessing potential health hazards from drugs in municipal wastewater. *Regul Toxicol Pharm.* 2011;60(1):1-19.

28. Rodriguez C, Cook A, Van Buyner P, Devine B, Weinstein P. Screening health risk assessment of micropollutants for indirect potable reuse schemes: A three tiered approach. *Water Sci Technol.* 2007;56(11):35-42.

29. Rodriguez C, Weinstein P, Cook A, Devine B, Van Buyner P. A proposed approach for the assessment of chemicals in indirect potable reuse schemes. *J Toxicol Env Health.* 2007; 70(19):1654-1663.

30. Snyder S, Trenholm R, Snyder M, Bruce GM, Pleus RC, Hemming JD. *Toxicological Relevance of EDCs and Pharmaceuticals in Drinking Water.* Denver, CO: American Water Works Association Research Foundation; 2008.

31. Snyder S, Benotti M, Rosario-Ortiz F, Vanderford B, Drewes JE, Dickenson E. *Comparison of Chemical Composition of Reclaimed and Conventional Waters Final Report.* Alexandria, VA: WateReuse Foundation; 2010.

32. Craun M, Craun G, Calderon R, Beach M. Waterborne Outbreaks Reported in the United States. *J Water Health.* 2006;4(2):19-30.

33. Asano T, Burton FL, Leverenz HL, Tsuchihashi R, Tchobanoglous G. *Water Reuse: Issues, Technologies and Applications.* New York: McGraw-Hill; 2007.

34. Craun GF. Causes of Waterborne Outbreaks in the United States. *Water Sci Technol.* 1991;24:17-20.

35. Tanaka H, Asano T, Schroeder ED, Tchobanoglous G. Estimating the Safety of Wastewater Reclamation and Reuse Using Enteric Virus Monitoring Data. *Water Environ Res.* 1998;70(1):39-51.

36. Orange County Water District. *Technical Memorandum on Microbial Water Quality.* Supplemental Report to the NWRI Groundwater Replenishment System Independent Advisory Panel; 2010.

37. Lozier JC, Kitis M, Kim JH, Mi B, Marinas BJ. Evaluation of Biologic and Nonbiologic Methods for Assessing Virus Removal By and Integrity of Pressure Membrane Systems. *In KJ Howe Edition: Membrane Treatment for Drinking Water & Reuse Applications: A Compendium of Peer Reviewed Papers*. Denver, CO: American Water Works Association; 2006:399-420.

38. California Department of Water Resources. Managing an uncertain future: Climate change adaptation strategies for California's Water. http://www.water.ca.gov/climatechange/docs/ClimateChangeWhitePaper.pdf. Published October 2008.

39. Smith KR, Jerrett M, Anderson HR, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: Health implications of short-lived greenhouse pollutants. *The Lancet.* 2009;374(9707):2091-2103.

40. Cole BL, Sokolow S. *Pu*blic Health impacts of urban water conservation in California: opportunities to maximize co-benefits and minimize harm with case-study analysis of water conservation in the city of Burbank. Prepared by the UCLA Fielding School of Public Health's Health Impact Assessment Project in collaboration with The Los Angeles County Department of Public Health http://www.ph.ucla.edu/hs/health-impact/reports.htm. Published 2014.

CHAPTER 2

Impacts of Urban Water Conservation Strategies on Energy, Greenhouse Gas Emissions and Health: Southern California as a Case Study*

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ABSTRACT

Climate change, increasing water demands, drought, and impaired water quality render water supply a critical issue across the world. In California, a state subject to serious drought, water use is linked to energy use and GHG emissions because most water is transported hundreds of miles from sources to users. Consequently, water conservation strategies in California have the potential to decrease carbon emissions and benefit human health. Here, we expand upon a comprehensive HIA of California's urban water conservation strategies, comparing the status quo to two options: (1) banning landscape irrigation, and (2) expanding alternative water sources (e.g., desalination, recycled water). Expanding recycled water use is a highly desirable option for California cities, because of its potential to reduce water use, energy use, and GHG emissions, with relatively small negative impacts on the public's health. Although the suitability of recycled water for urban uses depends on local climate, geography, current infrastructure, and finances, analyses similar to those presented here can help guide water policy decisions in cities across the globe that are facing challenges of supplying clean, sustainable water to urban populations.

INTRODUCTION

Water, energy, and health are intricately linked.[1-3] As a result, the health impacts of new water management policy and energy use policies and programs should be assessed systematically when programs and policies in these arenas are proposed, implemented, and evaluated. This is particularly true for the American Southwest and other locations with Mediterranean climates, including California, which is currently experiencing a prolonged drought and is projected to face even more dire water shortages going forward.[4-6] Our analysis will focus on Southern California as a model for how choices in water sources can impact human health.

To address the prospect of long-term water shortages, California implemented aggressive water conservation legislation ("The Water Conservation Act," Senate Bill x7-7), which calls for each of California's nearly 400 urban water districts to decrease water use by 20% by 2020.[7] In addition, during the 2014 election, California voters approved of a one billion dollar water bond, and in the Spring of 2015, California Governor Jerry Brown called upon urban water suppliers to cut water use by 25% from their 2013 usage levels.[8] The goal of each of these initiatives is to decrease demand for water across the state so that this demand is in better alignment with current and projected water resources. Senate Bill x7-7 mandates that each urban water district develop and implement a water management plan, but it does not specify how to achieve those reductions. Although the legislation does not mandate the mechanisms for reducing water use, it does list 14 "demand management measures" as suggested areas to focus water conservation actions.[9] Likewise, the governor's mandate requires urban water districts to conserve water, but does not specify how each district should achieve this goal.[8] In deciding which strategies to implement, urban water districts have a unique opportunity not only to decrease water

consumption overall, but also to implement those water conservation strategies that have secondary benefits to health.

To help urban water districts choose conservation strategies that maximize the potential health benefits and minimize potential harms to health, we recently completed an HIA of urban water conservation in California.[10] This work expands on our observation that the water-energy nexus is a source of negative health impacts, especially when coupled with climate change. Here, we discuss two different urban water conservation strategies that have the greatest potential to decrease energy use and GHG emissions in California: landscape irrigation bans and expanded use of alternative water sources (e.g., desalinated or recycled water). We discuss the health impacts of each of these strategies and compare them to the status quo. Based on this analysis, we recommend that urban water districts in California prioritize expansion of recycled water. Recycled water is a top priority because it not only conserves water, but also reduces energy consumption and GHG emissions, and thus has the largest potential to improve health. The positive impacts of increasing use of recycled water greatly outweigh potential negative impacts on health. Greater development of recycled water programs will provide a feasible solution to address the challenges of climate change by creating a new, sustainable, high quality water supply with the potential to sustain future increases in population. Although water recycling exists around the world, current levels of reuse only represent a fraction of treated wastewater generated and could be expanded immensely. We discuss the important role that public health professionals can play in helping their local water districts to adopt strategies that are conducive to both conserving water and improving the health of their constituents.

How California's current use of water impacts energy, GHG emissions, and health.

The majority of California's current water sources require high-energy inputs. Pumping, treating, transporting, and heating California's water currently account for nearly 20% percent of the energy used across the state.[6,11] Much of this energy use is the result of a heavy reliance on "imported" water, since the majority of the California's water users are concentrated far from major water sources.[1] One consequence of the energy used to transport California's water is high GHG emissions; transporting water via California's State Water Project alone uses 2-3% of the state's total energy and results in roughly 4 million tons of GHG emissions per year.[1,5]

Today, 750 million people worldwide (1 in 9 people) do not have access to safe and clean drinking water[12] — a number expected to increase with the onset of climate change, rising GHG concentrations, and increasing populations.[3] The energy intensity of California's water sources is troubling because climate change resulting from GHG emissions is projected to have substantial negative impacts on health, both locally and globally.[3] In California, some of the projected impacts of climate change on health include: (1) increased incidence of temperature-related illness and death, more air-pollution-related illness and death; (2) increased morbidity and mortality associated with sea level rise and wildfires; and (3) food and water shortages related to increasing temperatures, changes in precipitation patterns, and increased frequency of extreme weather events (**Figure 2-1**).[13]

California's reliance on imported water is also problematic because many of the state's sources of imported water are themselves threatened by climate change.[6] Climate change is projected to result in more extreme weather events, including more severe and frequent heat waves and

droughts.[3] Furthermore, increased temperatures will result in more precipitation as rain instead of snow in the American Southwest, and cause snow to melt earlier in the year.[6] These changes will reduce mountain snowpack, which serves as a natural storage system for fresh water and feeds springs and reservoirs as snow melts in the late spring and summer.[6] Water scarcity, which will be exacerbated by climate change, has additional negative health impacts.[13] Water scarcity often compromises nutrition as a result of diminished agricultural production.[13] Water scarcity can also result in reduced water quality due to saltwater intrusion or decreases in groundwater quality.[14] Secondary health impacts from water scarcity include respiratory and cardiovascular disease (e.g., from air quality issues arising from dry lake beds), as well as financial stressors that lead to poor health (e.g., stress, heart disease, exacerbation of illnesses) and morbidity and mortality related to insufficient or unclean water.[13,15-17] To make matters worse, some of these impacts will disproportionately affect California's more vulnerable populations (i.e., low income households and communities).[16,17]

Water scarcity also has implications for California's economy[18] that are inherently tied to human health.[16] In a future with increased water scarcity, water costs will rise. Water costs will rise not only due to smaller supplies and larger demands, but also because energy prices in California are predicted to rise by 80% over the next decade.[18] These increasing costs will undoubtedly disproportionately impact low income customers.[16] In California, 1 in 6 adults (6.3 million) and more than 1 in 5 children (2 million) lived in poverty in 2014.[19] For the lowest income populations, the amount of monthly income spent on housing and utilities and health care costs accounts for nearly 50% of the budget. In contrast, in higher income households, the amount of monthly income spent on housing, utilities, and health care costs accounts for 40% of the

budget.[19] Changes in water costs and availability will impact lower income households more profoundly since these households are already more financially strained and since a greater portion of their water use is for basic needs with little leeway for cuts in water use without impacting quality of life.[19]

Water shortages will also have implications for California's green spaces,[20] which play an important role in mediating health.[21] Without water to maintain green space and with temperatures already on the rise, there will be greater potential for extreme heat events and urban heat island effects.[22] Green space is an important mediator for the onset of climate change that can prevent health impacts related to heat stroke, respiratory disease, activity-related health impacts (obesity, heart disease), and mental and elderly health issues.[21,23-28]

Furthermore, each of the pathways discussed previously is compounded by California's expected population growth from 37 to 60 million people (a 162% increase) by 2050.[29] California's water sources are unsustainable for the current population and certainly cannot meet the needs of an expanding population if present per capita levels of water consumption continue. Solutions are needed that will allow California to move away from its current dependence on imported water. Ideally, water districts should adopt solutions that both decrease overall water use (i.e., conserve water) and also have fewer negative impacts on health. Subsequently, we examine two proposed urban water conservation strategies—landscape irrigation bans and expansion of alternative water sources—and discuss both of their downstream impacts on health.

METHODS

Identifying connections among water, energy, GHG emissions, and health.

We recently completed a comprehensive HIA of urban water conservation alternatives in California, which evaluates the linkages among urban water use, energy consumption, and public health.[10] HIA is a deductive science-based process of applying available research to specific policy questions, anticipating future impacts and incorporating the guidance of affected stakeholders. Like other HIAs, this HIA considered both potential benefits and potential harm of multiple pathways and impacts of a specific policy proposal, in this case, California Senate Bill x7-7[7], which mandated 20% reductions in urban water use by 2020. Specifically, this HIA aimed to identify the health impacts of different conservation measures available to utilities as they worked to achieve SBx7-7 targets.[10] Among the various health benefits and risks addresses in that HIA, health effects mediated by the energy needed for transporting and treating water from different sources stood out as both significant and under-appreciated. As a result of this finding, one of the report's main recommendations calls for the expansion of recycled water use; this conclusion is not only applicable to California, but also can be applied to water systems across the world.

Technical Advisory Committee.

This work was conducted with the guidance of a Technical Advisory Committee (TAC). The TAC included representatives from California's regional water wholesalers, municipal water suppliers, sanitation districts, state water regulatory boards, water conservation experts, and academics with expertise in the water-energy nexus, in addition to experts within California's state public health department. These individuals provided direction toward relevant literature to

support our work, as well as feedback regarding the applicability of our research and the feasibility of our recommendations.

Assessing energy demand.

Energy demand was an important part of our evaluation; the data used to determine energy demand for each water source were gleaned from several reports brought to our attention by TAC members. After identifying estimates of the amount of embedded energy in water from peer reviewed documents and water agency reports, we reviewed state-mandated urban water management plans for information on water sources used by different suppliers.[30-33] Realizing that each energy footprint of water deliveries is highly dependent on the location of a service area and each utility's unique mix of water sources, we created scenarios that appeared to have the most policy relevance to our geographic area, Southern California. For example, a groundwater aquifer close to the surface requires less energy than pumping from a deeper aquifer. During the course of the HIA, it became apparent that two conservation strategies could affect energy consumption and GHG emissions: landscape irrigation practices and the expansion of alternative water sources. These scenarios were chosen because changes in either water conservation strategy will impact the amount of imported water, and thus energy, needed throughout California.

Data analysis.

To analyze our data, we initially created a chart comparing the relative energy demand and GHG emissions **(Figures 2-2)**. Next, to build upon the extensive foundation of water and energy analysis from state agencies, water providers, and think tanks, we evaluated the peer-reviewed

literature **(Supplemental Table 2-1)**. We also held discussions with experts from the water community to build a theoretical framework of water sources, their energy demand, and how water uses can impact human health. Energy demands were selected using Southern California's West Basin Water District as a baseline, using minimum and maximum energy demand values to reflect the range. Although our specific example of energy intensity (**Figure 2-2**) focuses on conditions in Southern California, the intensity range for each water source helps show the applicability to other locations, and evaluating the extreme values does not change our conclusions. Thus, while the energy intensity of water sources outside Southern California may differ, this figure can be applied globally.

Using the data collected to create this energy demand chart (**Figure 2-2**), we were able to indicate cumulative magnitude of health impact from energy demand and costs associated with water sources by assigning a ranking (1-4) and calculating an average of the cumulative rank (**Figure 2-1)**. These data do not attempt to quantify the health impacts of climate change, but instead demonstrates the proportionate impact water source decisions can have on health.

GHG emissions were calculated based on annual average emissions factor for Southern California Edison (SCE; 0.32 kg CO2 equivalents per kwh) and median energy intensity for each water source.[32] Calculations for energy savings between California's State Water Project and recycled water were conducted using the State Water Project's annual water delivery of 230,000 AF/year,[1] and energy demand averaged from each water source: 3900 kwh/AF from the State Water Project and 385 kwh/AF from recycled water.

FINDINGS

Health impacts of landscape irrigation bans.

Landscape irrigation bans are an attractive water conservation strategy because irrigation consumes 52% of California's residential water use and is the single greatest component of urban water use in California overall.[34] Although some parts of the state irrigate large green spaces and golf courses with recycled water, many of California's urban areas do not currently have the infrastructure in place to use recycled water for irrigation.[35] This situation is not likely to change soon because it is very costly to install supplemental distribution systems for recycled water.[36] If California's current drought persists, mandatory irrigation restrictions could be implemented for urban parks. Similar mandates were put in place in many parts of Australia in the early 21st century in response to their severe drought.[20]

Landscape irrigation bans help conserve both water and energy, which can ultimately benefit health (**Table 2-1**). Specifically, eliminating water for landscape irrigation would decrease urban water districts' reliance on imported water, thereby reducing impacts from GHG emissions. These emission reductions would both benefit air quality[27] and reduce the effects of climate change.[13,23] In addition, decreasing urban water demand will increase the amount of water available for agricultural and environmental needs across the state and the Southwest region as a whole.[1]

While landscape irrigation bans would have a positive effect on lowering water and energy use, they could also result in negative impacts on human health. For instance, in Victoria, Australia, 50% of public parks and gardens halted irrigation due to water-use restrictions in 2007, which

reduced the presence of green space.[20] The absence of green space also has health implications related to activity. Diminished activity space is tied to exacerbation of activity-related illnesses such as obesity and heart disease, and can pose a disadvantage to individuals suffering from mental health issues, such as attention deficit hyperactivity disorder (ADHD).[25,26] The change in surface from green space to brown has been demonstrated previously to decrease physical activity and result in increased injuries that result from dry play areas.[37] Additional drawbacks include the loss of social capital from green spaces used as meeting points, decreased activity, and potentially exacerbating chronic illness in elderly populations.[21,25] Grass and trees provide beneficial ecological services, such as evapotranspiration, shading, and cooling of the surrounding environment.[24,38] Furthermore, decreasing levels of green space in urban areas exacerbates the impact of existing GHG emissions by trapping heat (i.e., the urban heat island effect) and promoting the creation of more harmful secondary pollutants.[36]

Less extreme versions of landscape irrigation bans include measures that promote or require xeriscaping (i.e., landscaping using low-water, drought tolerant plants[35]). Xeriscaping has the potential to be a particularly valuable conservation tool in Southern California because 65% of residential water use in a typical Southern Californian home is used in outdoor irrigation.[39] Although xeriscaping is effective in lowering outdoor residential water use, it can also result in negative health impacts. An Arizona study determined that soil temperatures in xeriscaped sites were 8 degrees Celsius higher than under turf.[35] Likewise, this study found that dense green space in urban neighborhoods reduced energy needs for cooling by 3.5% compared to a reduction of 0.4% with minimal green space.[38]

The negative health impacts resulting from reducing green spaces have been shown in the past to impact vulnerable populations differentially. For instance, decreases in the ratio of green space-to-pavement has been shown to lead to higher temperatures in poorer areas than in more affluent neighborhoods, causing a more pronounced increase in extreme heat events and exacerbation of urban heat island effects in low-income neighborhoods.[40]

Health impacts of expanding use of alternative water sources.

Increased use of local groundwater extraction, desalination, and expanded recycled water use have all been suggested as ways to help meet California's urban water needs and shift reliance away from use of imported water. Shifting to alternative water sources has the potential to lower GHG emissions and impact human health positively **(Table 2-2)**; however, the energy intensity varies tremendously among specific alternative water sources. For instance, production of desalinated water is more energy intensive than importing water **(Figure 2-2**).[1,33] The energy required to operate an ocean desalination facility is nearly 50% higher than California's next most energy-intensive source of water (imported water) and more than 120 times more energy-intensive than getting water from the gravity-powered Los Angeles Aqueduct.[30,41] Furthermore, although infrastructure exists for operation of 17 desalination plants in California, none are in operation due to environmental concerns.[42]

Although desalination has been deployed successfully in both Australia and Israel[43], this does not necessarily mean desalination is a good solution for California. Emissions related to the high energy demands of desalination would exacerbate poor air quality and respiratory disease in California. As a result of existing air quality problems, California holds the most strict air quality

standards in the United States and has implemented penalties for excessive emissions.[44] Due to these penalties, the cost of desalinated water in California will be much more expensive than in either Australia or Israel. However, as desalination technology improves and becomes more energy efficient, desalinated water may become a viable option for California in the future.[33]

By contrast, increasing the use of groundwater as an alternative source of water in California would be less energy intensive than our current use of imported water (**Figure 2-2**).[1,30] In 2014, as a result of California's severe drought, water districts relied on groundwater to supplement an unprecedented 60% of the potable water supply in the state compared to ~30% in non-drought years.[14] This increased reliance on groundwater has had implications for human health;[14] many existing groundwater basins are contaminated, and the extent of contamination is exacerbated during drought periods. Without natural waters to recharge the basins during drought periods, contaminants in the groundwater become more concentrated; exposure to these contaminants can lead to increased rates of gastrointestinal illness and cancer.[45,46]

Recycled water is much less energy intensive than desalination, imported, water or groundwater (**Figure 2-2**),[30] and poses fewer real health risks. Increasing the percentage of recycled water used in California would substantially decrease GHG emissions, which would have a dramatic positive impact on human health. If just 10% of the water that is currently imported from the State Water Project were shifted to recycled water, California would save ~80 million kWh of energy annually and reduce carbon emissions by nearly 42,000 metric tons per year.

Increasing use of recycled water throughout California would have significant health benefits. At a minimum, recycled water could be used more extensively to maintain green spaces, which would reduce urban heat island effects, and hence limit the severity of extreme heat events. In Southern California, the Burbank Water District implemented recycled water systems to irrigate all parks during the 1980s.[47] Although this involved initial infrastructure costs, Burbank's green spaces are protected from potential landscape irrigation bans, thus maintaining ecological services and health benefits for the surrounding area. Recycled water could also be expanded to recharge groundwater basins, which would result in a net improvement in groundwater quality by helping to dilute potential contaminants.[14] Recycled water is cheaper than other alternatives[31], which would render a positive impact on utility costs to benefit low-income households.

DISCUSSION AND IMPLICATIONS

Based on recommendations from our comprehensive HIA of urban water conservation strategies[10], and our further evaluation of health impacts of the water-energy nexus, we find that expanded recycled water use is an attractive alternative to imported water in California. Recycled water use has great potential for expansion because its water source (wastewater) is in abundant supply, has lower marginal costs, and has a smaller energy footprint than imported water or desalination. Nonetheless, recycled water is underutilized in California.[48] In 2009, wastewater treatment systems in the South Coast Basin hydrologic region (Los Angeles and surrounding areas) treated 1.5 million AF of wastewater.[49,50] Of this, just 176,000 AF (11%) were allocated for uses that required potable water, and 1.32 million AF (89%) were discharged into the ocean.[49,50] Clearly, for expansion of recycled water to occur, more effort than just a bill promoting water conservation is needed. When determining which water conservation measure

to use, our study shows that when choosing recycled water over other alternatives, health benefits increase overall, and are specifically maintained for green spaces; in addition, GHG emissions lower and water conservation increases.

Worldwide, lessons from water recycling in California would be valuable across the United States, especially in the Southwest and Southeast, and in higher-income countries within subtropical latitudes where precipitation is predicted to decrease, such as the Mediterranean, parts of Mexico and Central America, and Australia. In most locations, infrastructure, not water treatment technology, is the barrier to recycled water expansion. In areas with growing populations and expanding infrastructure, adaptations for recycled water piping should be implemented during initial construction stages, even if recycled water has not yet been authorized, as retrofits can be cost prohibitive. Lessons from our study lose relevancy in high latitude areas, such as India and parts of Central Asia where climate change is predicted to increase precipitation heavily, and in low-income countries where adaptations to water systems are not financially feasible.

Subsequently, we discuss three categories of barriers to expanded use of recycled water—public perceptions, regulatory, and financial barriers—and the potential roles that public health professionals can play in lowering these barriers and hence improving the health of the communities that they serve.

Lowering public perception barriers to expanded recycled water use.

Public perception is currently a barrier to expansion of recycled water, even though current technologies can treat wastewater cost-effectively to levels that exceed federal health standards for potable water.[51] Review of successful, recycled water programs in Orange County, California and in Singapore (two large-scale urban settings) can provide insights into how problems related to public perceptions were overcome. In both of these cases, local governments opted to use recycled water to replenish water supplies *indirectly*, thus removing problems associated with public stigmatization of *toilet to tap*. In the case of Orange County's Groundwater Replenishment System (GWRS), recycled water is pumped into Orange County's groundwater basin, which then becomes available for use.[52] The GWRS supplies 72,000 AF/year of potable water, enough to supply the water needs of 600,000 people.[52] Singapore has a more comprehensive system, known as NEWater, that collects and treats 100% of that nation's wastewater.[53] Currently, Singapore allocates 56,000 AF/year for industrial and commercial uses.[53] After treatment, this water is placed in a reservoir, where it is mixed with fresh water for domestic use.[53]

As discussed previously, substantial opportunities exist in California to use recycled water to recharge groundwater and for outdoor irrigation, which could result in dramatic reductions in the use of imported water across the state. Public health professionals can play a critical role in promoting the health benefits of these strategies by collaborating closely with their local water districts to move these efforts forward. For instance, there is clearly a need for local health departments to help develop educational, culturally sensitive campaigns for the general public promoting appropriate use of recycled water that are both based on the latest science.

Lowering regulatory barriers to expanded recycled water use in California.

Although water regulations in California currently allow for indirect potable reuse (IPR) of water[54], direct potable reuse (DPR) of treated water would be more cost and energy effective and hence more desirable in the long run. To this end, a bill was passed in California (SB 322 (Hueso), 2013) that requires that State Department of Public Health "to investigate the feasibility of developing uniform water recycling criteria for DPR and to provide a final report on that investigation to the Legislation on or before December 31, 2016."[55] Public health professionals can stay abreast of progress on this issue by visiting the State Water Resource Control Board's Division of Drinking Water's Recycled Water website: http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/RecycledWater.shtml

Lowering financial barriers to expanded recycled water use in California.

Another barrier to increased use of recycled water is upfront infrastructure costs.[48] California's 2014 water bond allocates $725 million towards recycled water projects. Finances provided by the water bond are one mechanism by which to lower the costs of implementing large scale systems for purification and distribution of recycled water across the state[56] and help to make these costs competitive with the substantial costs associated with maintaining California's current levels of imported water.[1] In addition, researchers have recently demonstrated the feasibility of a system for residential graywater treatment that would allow individual households to treat and reuse water onsite, obviating the need for expensive, municipal-level recycled water distribution systems.[57]

CONCLUSION

California's current drought has inspired increased urgency for innovative drought solutions. Wise, effective action can help make future reductions easier without compromising the economic, quality of life, and health benefits provided by water. Decreases in per capita water consumption are an important part of efforts to bring demand in line with supply. Using a comprehensive HIA approach, we demonstrate that expanded use of recycled water in California, in addition to being an effective water conservation strategy, would result in health benefits. This is primarily because expanded use of recycled water would dramatically reduce energy consumption and GHG emissions associated with urban water consumption, as well as because recycled water can be used to promote green spaces for recreational uses and to mitigate urban heat island effects. Ironically, public health concerns have traditionally been a barrier to expansion of recycled water, even though the risks associated with recycled water use do not exceed those found in traditional water supplies. Public health professionals can play an important role in promoting the health benefits of recycled water and by working with colleagues in other sectors to advance the safe and appropriate expansion of recycled water use.

REFERENCES FOR CHAPTER 2

1. Cohen R, Nelson B, Wolff G. Natural Resources Defense Council. Energy down the drain: The hidden costs of California's water supply. https://www.nrdc.org/water/conservation/edrain/edrain.pdf. Published 2004.
2. Smith KR, Jerrett M, Anderson HR, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants. *Lancet.* 2009;374(9707):2091-2103.
3. Intergovernmental Panel on Climate Change. Climate change 2013: The physical science basis. https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WGIAR5_SPM_brochure_en.pdf. Published October 2013.
4. California Department of Water Resources, State of California, The Resources Agency. Preparing for California's next drought: Changes since 1987-1992. http://www.water.ca.gov/waterconditions/docs/Drought_Report_87-92.pdf. Published July 2000.
5. California Department of Water Resources. Climate action plan. Phase 1: Greenhouse gas emissions reduction plan. http://www.water.ca.gov/climatechange/docs/Final-DWR-ClimateActionPlan.pdf. Published May 2012.
6. California Department of Water Resources. *Managing an Uncertain Future: Climate Change Adaptation Strategies for California's Water.*
7. California State Senate. *Senate Bill x7-7: An act to amend and repeal Section 10631.5 of, to add Part 2.55 (commencing with Section 10608) to Division 6 of, and to repeal and add Part 2.8 (commencing with Section 10800) of Division 6 of, the Water Code, relating to water.* November 10, 2009.

8. California Government Code Executive Order No. B-29-15. 2015.

9. California State Assembly. Assembly Bill 42: An act to amend Sections (10631.5) and (10644) of and to add Section (10631.7) to the Water Code relating to water. 2007.

10. Cole BL, Sokolow S. Public health impacts of urban water conservation in California: Opportunities to maximize co-benefits and minimize harm with case-study analysis of water conservation in the city of Burbank. Prepared by the UCLA Fielding School of Public Health's Health Impact Assessment Project in collaboration with The Los Angeles County Department of Public Health http://www.ph.ucla.edu/hs/health-impact/reports.htm. Published 2014.

11. California Energy Commission. *Final Staff Report, California's Water-Energy Relationship, CEC-700-2005-011-SF*. 2005.

12. World Health Organization and UNICEF. Progress on drinking water and sanitation 2014 update. http://www.wssinfo.org/fileadmin/user_upload/resources/JMP_report_2014_webEng.pdf Published 2014.

13. Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. Impact of regional climate change on human health. *Nature.* 2005;438(7066):310-317.

14. California Department of Water Resources. Public update for drought response: Groundwater basins with potential water shortages and gaps in groundwater monitoring. http://www.water.ca.gov/waterconditions/docs/Drought_Response-Groundwater_Basins_April30_Final_BC.pdf. Published 2014.

15. Gleick PH, Pacific Institute. Dirty water: Estimated deaths from water-related diseases 2000-2020. http://www.pacinst.org/wp-

content/uploads/sites/21/2013/02/water_related_deaths_report3.pdf. Published August 2002.

16. Wilkinson R. *Unhealthy Society: The Affliction of Inequality.* London: Routledge; 1997.

17. McDonough P, Duncan, GJ, Williams, D, House, J. Income dynamics and adult mortality in the United States, 1972-1989. *Am J Public Health* 1997;87(1476-83).

18. Boxall B. Water's energy -- and expense. *Los Angeles Times.* November 14, 2011.

19. California Budget Project. Making ends meet: How much does it cost to raise a family in California? http://calbudgetcenter.org/wp-content/uploads/131212_Making_Ends_Meet.pdf. Published 2013.

20. Chong J, Herriman, J, White, S, Campbell D, Institute for Sustainable Futures and ACIL Tasman. Review of water restrictions volume 1: Review and analysis. Final report For National Water Commission of Australia. http://archive.nwc.gov.au/__data/assets/pdf_file/0019/11755/Water_restrictions_Volume_1.pdf. Published 2009.

21. Maas J, Verheij, RA, Groenewegen, PP. de Vries, S, Spreeuwenberg, P. Green space, urbanity, and health: How strong is the relation? *J Epidemiol Commun H.* 2006;60(7):587-592.

22. McPherson E, Simpson, JR, Peper PJ, Xiao, Q, Center for Urban Forest Research USDA Forest Service. Benefit-cost analysis of Santa Monica's municipal forest. http://www.fs.fed.us/psw/programs/uesd/uep/products/cufr47_SMonicaBCA.pdf. Published November 2001.

23. Wilby R. Constructing climate change scenarios of urban heat island intensity and air quality. *Environ Plann B.* 2008;35(5):902-919.

24. Basu R, Samet, J. Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. *Epidemiol Rev.* 2002;24:190-202.

25. Gladwell V, Brown, DK, Wood, C, Sandercock, GR, Barton, JL. The great outdoors: How a green exercise environment can benefit all. *J Extreme Physiol Med.* 2013;2(3).

26. Kuo F, Taylor, FE. A potential natural treatment for attention deficit/hyperactivity disorder: Evidence from a natural study. *Am J Public Health.* 2004;94(9):1580.

27. Nowak D, Crane, DE, Stevens, JC. Air pollution removal by urban trees and shrubs in the United States. *Urban For Urban Gree.* 2006;4:115-123.

28. Jennings V, Gaither, CJ. Approaching Environmental Health Disparities and Green Spaces: An Ecosystem Services Perspective. *Int J Env Res Pub He.* 2015;12(2):1952-1968.

29. State of California Department of Finance. Interim population projections for California and its counties 2010-2050. http://www.dof.ca.gov/research/demographic/projections/2012. Published 2012.

30. Wilkinson R. Analysis of the energy intensity of water supplies for West Basin Municipal Water District. http://www.westbasin.org/files/general-pdfs/Energy--UCSB-energy-study.pdf. Published March 2007.

31. Raucher R, Tchobanoglous G. The opportunities and economics of direct potable reuse. WateReuse Foundation: https://www.watereuse.org/product/14-08-1. Published 2014.

32. State of California. State agency greenhouse gas report card. http://www.climatechange.ca.gov/climate_action_team/reports/2013_CalEPA_Report_Card.pdf. Published January 2013.

33. Cooley H, Heberger, M; Pacific Institute. Key issues for seawater desalination in California: Energy and greenhouse gas emissions. http://pacinst.org/wp-content/uploads/sites/21/2013/05/desal-energy-ghg-full-report.pdf. Published 2013.

34. California Department of Water Resources. Chapter 3. Urban water use efficiency, California water plan update. http://www.water.ca.gov/calendar/materials/vol3_urbanwue_apr_release_16033.pdf. Published 2013.

35. Addink S, University of California Riverside Turfgrass Research Facility. Cash for grass - A cost effective method to conserve landscape water. https://agops.ucr.edu/turf/topics/Cash-for-Grass.pdf. Published 2005.

36. Fam D, Mosley E, Lopes A, Mathieson L, Morison J, Connellan G. CRC for Irrigation Futures Technical Report. Irrigation of urban green spaces: A review of the environmental, social and economic benefits. http://www.irrigationfutures.org.au/imagesDB/news/CRCIF-TR0408-web-final.pdf. Published April 2008.

37. Takemura M, Schneiders AG, Bell ML, Milburn PD. Association of ground hardness with injuries in rugby union. *Brit J Sport Med.* 2007;41(9):582-587.

38. Jo H, McPherson EG. Indirect carbon reduction by residential vegetation and planting strategies in Chicago, USA. *J Environ Manage.* 2001;61(2):165-177.

39. DeOreo WB, Mayer PW, Martien L, et al., California Department of Water Resources. California single family water use efficiency study (sponsored by the California Department of Water Resources). http://www.irwd.com/images/pdf/save-water/CaSingleFamilyWaterUseEfficiencyStudyJune2011.pdf. Published 2011.

40. Buyantuyev A, Wu, J. Urban heat island and landscape heterogeneity: linking spatiotemporal variations in surface temperatures to land-cover and socioeconomic patterns. *Landscape Ecol.* 2010;25:17-33.

41. California Sustainability Alliance. The role of recycled water in energy efficiency and greenhouse gas reduction: Appendix E: Water agency profile: City of Los Angeles. http://sustainca.org/sites/default/files/FINAL APPENDIX E MAY 2 2008.pdf. Published 2012.

42. Fagan K. Desalination plants a pricey option if drought persists. *San Francisco Gate.* February 15, 2014.

43. Tal A. The desalination debate -- Lessons learned thus far. *Environ: Sci Pol Sust Dev.* 2011;53(5):34-48.

44. California State Assembly. *Assembly Bill 32: California Global Warming Solutions Act.* 2006.

45. Mott L, Fore D, Curtis J, Solomon G, Natural Resources Defense Council. Our children at risk: The five worst environmental threats to their health; Chapter 7: Drinking water contamination. http://www.nrdc.org/health/kids/ocar/chap7.asp. Published 1997.

46. Cook A, Devine B, Rodriguez C, et al., Department of Water Government of Western Australia. Assessing the public health impacts of recycled water use. http://www.water.wa.gov.au/PublicationStore/first/107561.pdf. Published 2008.

47. Burbank Water and Power. 2010 urban water management plan. https://www.burbankwaterandpower.com/images/water/downloads/Burbank2010UWMP_web.pdf. Published 2010.

48. Newton D, Balgobin D, Badyal D. State Water Resources Control Board. Results, challenges, and future approaches to California's municipal wastewater recycling survey.

http://www.waterboards.ca.gov/water_issues/programs/grants_loans/water_recycling/docs/article.pdf. Published 2010.

49. Sutula MA, Lyons GS. Southern California Coastal Water Research Project. 2011 SCCWRP Annual Report: Effluent discharges to the Southern California Bight from large municipal wastewater treatment facilities from 2005 to 2009. http://ftp.sccwrp.org/pub/download/DOCUMENTS/AnnualReports/2011AnnualReport/ar11_223_236.pdf. Published 2011.

50. California State Water Resources Control Board. Water recycling funding program, municipal wastewater recycling survey. http://www.waterboards.ca.gov/water_issues/programs/grants_loans/water_recycling/munirec.shtml. Published 2011.

51. Toze S. Water reuse and health risks, real vs. perceived. *Desalination.* 2006;187(1):41-51.

52. Orange County Groundwater Replenishment System. Groundwater replenishment system technical brochure. http://www.gwrsystem.com/. Published 2015.

53. Tortajada C. Water Management in Singapore. *Int J Water Resour D.* 2006;22(2):227-240.

54. California State Water Resources Control Board. *Title 22 Water Regulations.* 2014.

55. Hueso B. *Senate Bill 322: An act to amend Sections 13563, 13564, 13565, and 13569 of the Water Code, relating to water recycling.* 2013.

56. California State Assembly. *Assembly Bill 1471: The Water Quality, Supply and Infrastructure Improvement Act of 2014 that passed November 4, 2014 general election as Proposition 1.* 2014.

57. Yu ZLT, Rahardianto A, DeShazo JR, Stenstrom MK, Cohen Y. Critical review: Regulatory incentives and impediments for onsite graywater reuse in the United States. *Water Environ Res.* 2013;85(7):650-662.

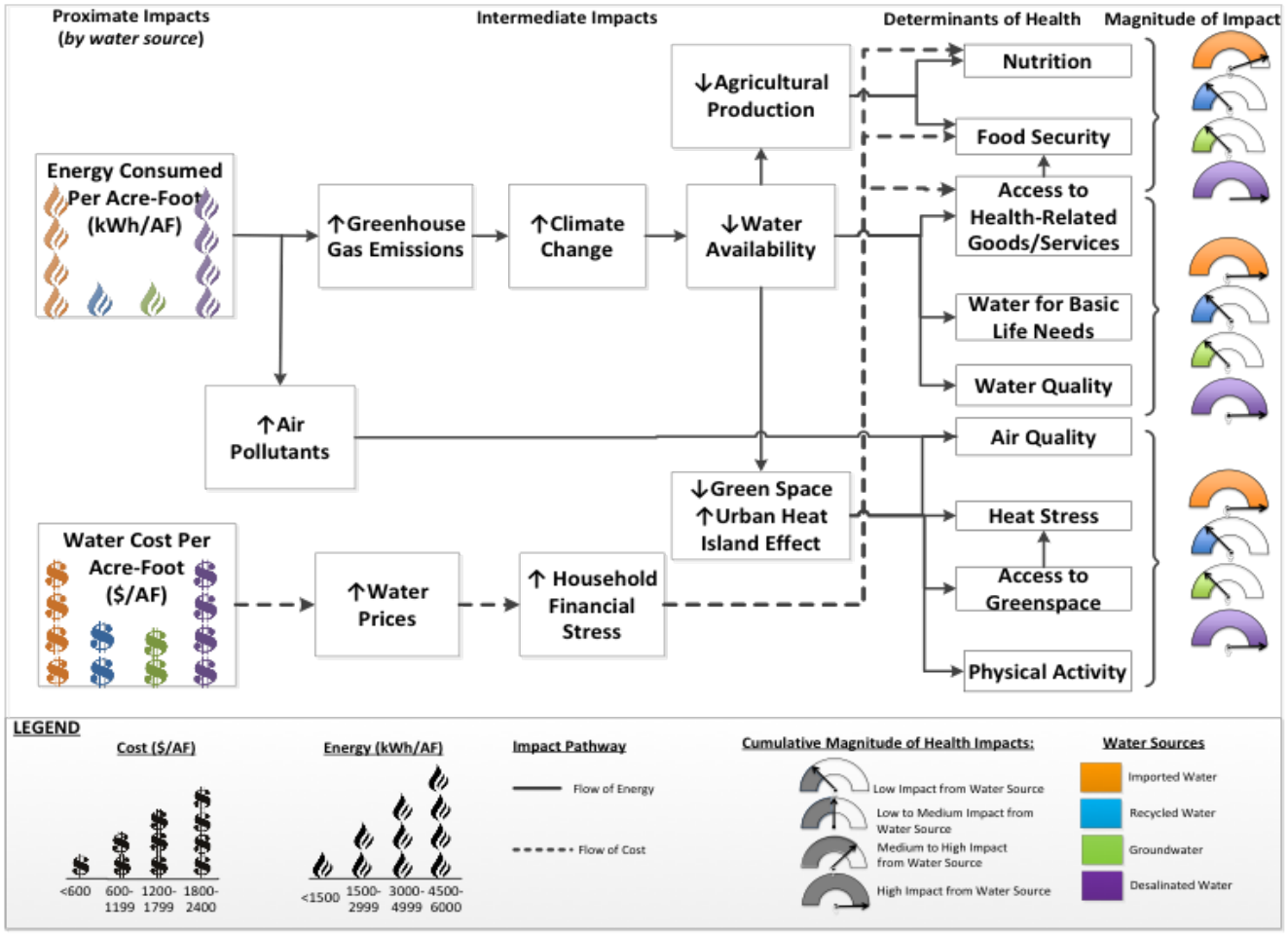

Figure 2-1: Water sources have differing impacts on human health. Water source decisions will impact human health in a variety of ways, especially when compounded by climate change and population rise. Water sources with lesser energy and cost demand (recycled water and groundwater) have a lower cumulative magnitude of impact on human health than those with higher energy and cost demand (desalination and imported water). Water sources such as desalination and imported water have a higher potential to affect health outcomes from the energy/cost pathway. AF= acre-foot = 325,853 gallons of water.

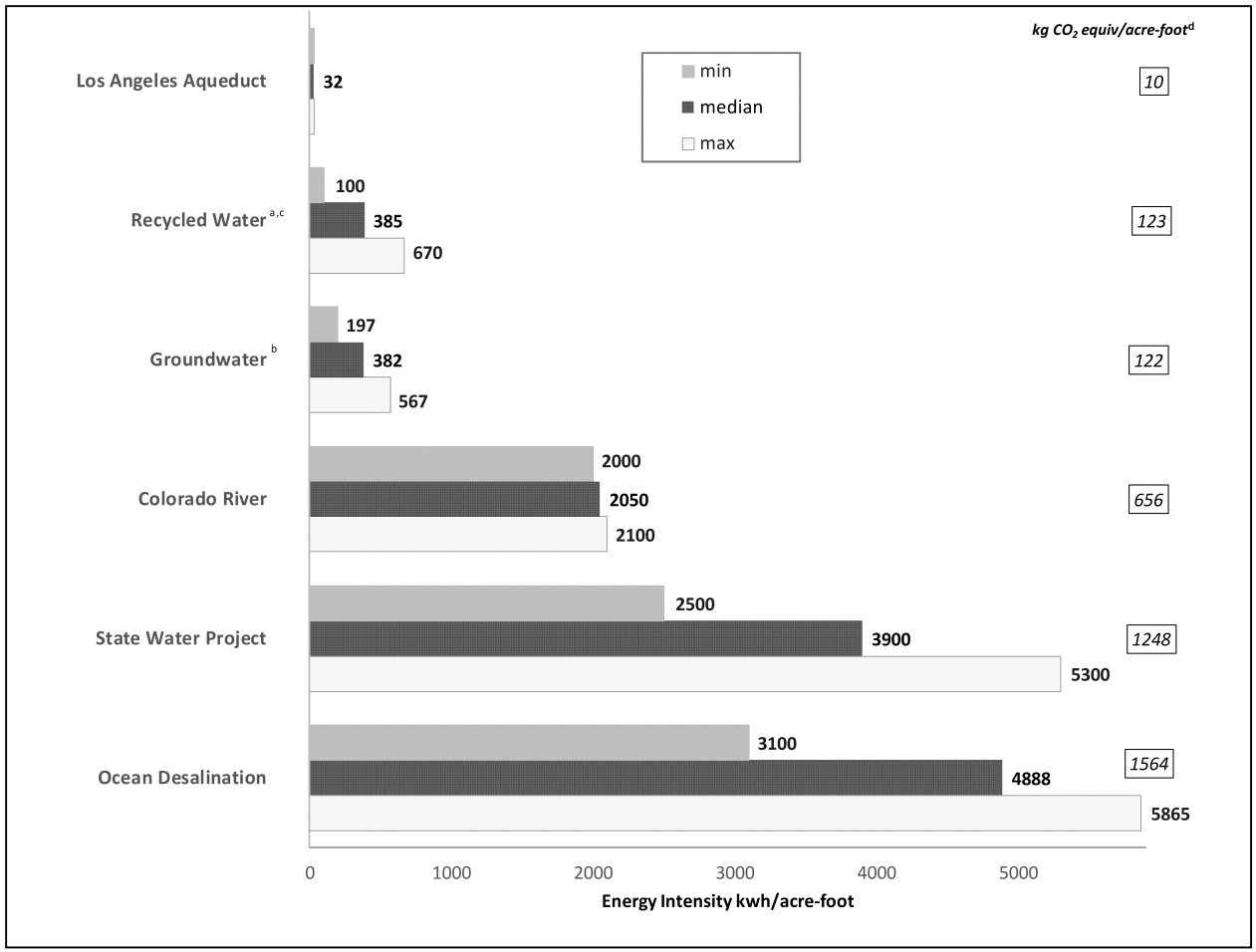

Figure 2-2: Energy intensity of California's water sources. Whereas recycled water and Local Groundwater are much less energy intensive than water imported via the State Water Project West Branch or the Colorado River, Ocean Desalination is currently *more* energy intensive than these two sources of imported water and thus correspond increased greenhouse gas emissions per acre foot of water[28-31]. Substituting recycled water for water from these two sources of imported water would significantly decrease energy consumption and greenhouse gas emissions in California and hence benefit health.

[a]For recycled water systems, energy recovery is not included. For plants that are 10 Mgal/d and larger, the potential energy recovery from biogas is on the order of 115 kWh/AF, potentially offsetting energy needed to treat and distribute water [29]

[b]Groundwater is pumped from differing depths depending on location, this estimate is based on the West Basin Water District in Southern California[28].

[c]The low value for recycled water is based on West Basin Water District in Southern California whose distribution system uses gravity to deliver the recycled water[28].

[d]GHG emissions based on annual average emissions factor for Southern California Edison (0.32 kg CO2 equivalents per kwh) and median energy intensity for each water source[30].

Table 2-1: Positive and negative impacts of landscape irrigation bans

Health Impact Area	Implications	Health Impact
Energy Use	Increased greenhouse gas emissions	↑Respiratory Disease, ↓Air Quality, ↑Extreme Heat Events, ↑Heat Stroke Exacerbation of illnesses
Elimination of Green Space (for ecosystem services)	Vegetation dies, changes in albedo and urban heat island effect; change in activity surface	↑Respiratory Disease, ↓ Air Quality, ↑ Extreme Heat Events, ↑ Heat Stroke; ↑ Sports Injuries
Elimination of Green Space (for activity)	Less space for activity	↑ Activity-related illnesses (obesity, cardiovascular disease); Exacerbation of mental health issues ↓ Social interaction ↓ Elderly Health

Table 2-2: Positive and negative health impacts of alternative water sources

Health Impact Area	Implications	Health Impact
Water Quality	Increased Groundwater Pumping; Wastewater treatment level	↑ Gastrointestinal illnesses ↑ Cancers
Energy Use	Increased Greenhouse Gas Emissions	↑Respiratory Disease, ↓Air Quality, ↑Extreme Heat Events, ↑Heat Stroke
Water Cost	Changes in water availability (and source) will be reflected in water cost	↑ Financial Stressors
Presence of Green Space	Vegetation dies, changes in albedo and urban heat island effect, change in activity surface	↑Respiratory Disease, ↓ Air Quality, ↑ Extreme Heat Events, ↑ Heat Stroke, ↑ Sports Injuries

CHAPTER 3

Assessing Health Impacts of Direct Potable Reuse for the Urban Water Supply: Case Study of Long Beach, California.

ABSTRACT

Use of recycled water is emerging as one strategy to help close the gap between potable water demand and increasingly limited, unstable water supplies.[1,2] Numerous studies have investigated the potential health risks related to use of recycled water,[3-10] but few studies have focused on potential health-related associated with increased use of recycled water.[11,12] Here, we provide a framework for holistically assessing the potential health risks and benefits of recycled water for potable use compared to established water source options (i.e., imported water, groundwater, recycled water for non-potable reuse, seawater desalination). For illustrative purposes, we have applied this framework to a case study of the LBWD in Southern California. We qualitatively evaluated the sustainability, technical feasibility, water quality, and public perception of current and proposed water sources for LBWD. We also modeled energy demand, GHG emissions, and costs of four different water source scenarios for LBWD in 2025 and 2035. This process highlighted existing uncertainties and data gaps that would need to be addressed for the impacts of water source choices to be evaluated more rigorously. Although the results are specific to Long Beach, the framework should be useful to stakeholders making urban water management decisions in a variety of contexts. Proactively assessing the potential health-related impacts of water source decisions can provide local water districts and decision makers with information to

minimize harm and maximize health-related benefits while choosing which water sources are the best fit to local circumstances.

INTRODUCTION

Traditionally, water source choices have been justified primarily on the relative costs, technical feasibility, and public perception of different water source options.[13] More recently, concerns about climate change have highlighted the importance of also considering the sustainability, energy demand, and associated GHG emissions of different water sources.[13] By contrast, relatively few studies have examined the health impacts of water source management decisions.[3,7-10,14-21]

In those cases where studies analyzing water source management decisions *have* included assessments of health impacts, they have focused primarily on concerns about water quality, particularly in situations where recycled water has been considered as a water source.[3,7-10,19-24] Fears that recycled water is unclean, or that it may cause disease, have been a major impediment to use of recycled water in some areas.[14-18] For instance, in San Diego in the 1990s, public fears over the use of recycled water fueled opposition to a water reuse facility, and eventually contributed to abandonment of the original proposed project.[17,25,26]

Health risks linked to waterborne contaminants depend on the eventual end use for the reclaimed water, since both the required treatment technology and the potential for exposure depends upon the intended use of the water.[19,22-24,27] A primary concern about the use of recycled water for *potable* applications is that recycled water may contain microbial pathogens, viruses, or trace

organic chemicals that have the potential to affect human health.[19,20] Pathogens are of particular concern because of their acute human health effects; viruses require special attention because of their low infectious dose, and because their small size may pass unimpeded through water treatment processes.[19,22-24] By contrast, concerns about contaminants found in reclaimed water tend to be lower in industrial or irrigation applications because the potential for human dermal or inhalation exposure is less likely.[19,22,23,27]

Despite widespread concerns about the safety of recycled water, several prior studies have suggested that health concerns about recycled water are minimal if the water is recycled with appropriate treatment technologies. For instance, rats and mice that were exposed to varying concentrations of recycled water treated for potable reuse (i.e., treated to potable standards through ultrafiltration, reverse osmosis, ozone disinfection, and/or granular activated carbon and then diluted with municipal drinking water) have not shown any signs of reproductive, developmental, or chronic toxicity.[4,5] Likewise, fish exposed to concentrated recycled water over multiple generations resulted in no statistically significant differences in mortality, morphology, reproduction, or offspring sex ratios.[6] A report by the National Research Council (NRC) used quantitative comparative risk assessment to determine potential risk associated with specific contaminants that may be present in recycled water treated for potable reuse.[3] The potential contaminants assessed included pharmaceuticals, personal care products and classes of contaminants including disinfection byproducts (DBPs), hormones, pharmaceuticals, and antimicrobial compounds. The NRC assessment concluded that the levels of contaminants found in recycled water treated by a combination of microfiltration, reverse osmosis, and advanced oxidation do not exceed levels in existing fresh potable water supplies.[3,7-10,21] Taken together,

these and other studies suggest that expanded use of recycled water—if treated appropriately for potable reuse—would contribute relatively little to the total United States disease burden.[3-5,20]

In contrast to the extensive research on the potential health risks of recycled water use, relatively few studies have focused on any potential health-related benefits of increasing use of recycled water.[11,12] Climate change is projected to result in increasingly unpredictable weather patterns going forward, which will make it that much harder to support growing water demands due to population growth, particularly in areas like Southern California that already experience water scarcity.[28-31] Worldwide, increased water insecurity is responsible for some of the largest projected impacts of climate change on human health.[32,33] Water scarcity often compromises nutrition as a result of diminished agricultural production, and reduced water quality due to salt-water intrusion into the root zone or decreases in groundwater quality.[34] Secondary health impacts from water scarcity include respiratory and cardiovascular disease (e.g., from air quality issues arising from dry lake beds, such as inhalation of airborne dust), as well as financial stressors that lead to poor health (e.g., stress, heart disease, exacerbation of illnesses) and morbidity and mortality directly related to insufficient or unclean water.[32,35-37] Recent studies have shown that expanded use of recycled water can help to reduce demand for fresh water, and can also reduce energy consumption and GHG emissions, which can constitute a valuable contribution to efforts to mitigate climate change.[11,12]

Methodologies are needed that allow decision makers to account explicitly for both health benefits and health risks of water source choices and weigh these health factors alongside factors related to sustainability, technical feasibility, water quality, public perception, energy demand,

GHG emissions, and cost considerations of different water supplies. (**See Figure 3-1**.) To this end, we have developed a framework for evaluating how factors related to water sources decisions may impact health. We focus on the application of this framework to a specific case study, namely water source decisions for LBWD in Southern California. Although the results from the case study are specific to LBWD, the approach demonstrated herein could be used by decision makers to assess the health impacts of water source decisions in a variety of contexts.

METHODS

HIA methodology.

We drew upon HIA methodologies to build a structured framework to evaluate water source decisions and their potential to influence health (**see Figure 3-2**). HIA aims to determine the range and magnitude of both positive and negative, as well as both intended or unintended, health-related impacts of proposed policies or projects.[38,39] HIA methodology recognizes the complex interactions that are not traditionally considered (e.g., the health-related impacts of air pollution stemming from increases in energy demand) that may result in unique health-related outcomes for differing populations.[38-40] HIA employs a multi-disciplinary approach to distinguish between these interactions and connections. This process typically involves consultation with a diverse group of experts outside of public health and medicine and review of research literature from different areas and methodologies.[38-40] The analysis reported here did not involve conducting a full HIA and did not investigate the health impacts of a specific policy or project. However, we did apply HIA methodology to identify the potential health impacts from water source decisions for local water districts. Since this study focused on LBWD in Southern California, the conclusions drawn herein are specific to this particular case study. The framework

and methodology reported here could, however, be used by other water districts or agencies that wish to understand the health impacts of their local water source decisions.

Development of the logic framework: literature review and discussions with experts.

To illustrate both confirmatory and disconfirmatory evidence for the putative linkages between water source decisions and health, we developed a logic framework based on a synthesis of information available in the peer-reviewed and gray literature and through conversations with experts in the field (**see Figure 3-2**). We used Google Scholar and Web of Knowledge to review peer-reviewed literature using search terms such as "water quality AND health," "climate change AND air quality," "household budget AND health," "wastewater AND health concerns," and "air quality AND energy demand." To identify reports from agencies, non-profit organizations, and local water districts, we used Google and Google Scholar search terms such as "sustainability AND California water," "climate change AND California water." We also explicitly identified data from relevant water agency websites, such as Southern California's Metropolitan Water District (MWD) and LBWD. Additionally, conversations with experts from California's regional water wholesalers, municipal water suppliers, sanitation districts, and public health experts were used to help guide the analysis. These individuals identified relevant literature and data sources to support our work. The experts also played a critical role in delivering feedback regarding the applicability of our research and the feasibility of our recommendations.

Case study: Southern California's Long Beach Water District.

To validate the utility of the framework presented herein, we applied our framework to a case study at LBWD. LBWD was selected for the case study because, unlike most other California water districts, LBWD's boundaries generally correspond to the city's boundaries.[41] Thus, water services, wastewater collection and treatment, and water use policies all apply to the same geography and population, which theoretically allows for geographic coordination across services and greatly simplified our analysis. LBWD currently uses three of the five water sources described within this report (imported water, groundwater, recycled water for non-potable reuse). According to the LBWD Urban Water Management Plan, LBWD proposes to reduce imported water by 2025 by implementing desalination, albeit on a limited scale.[41] LBWD does not currently have plans for using reclaimed water for potable applications. Hence, an analysis that compares the potential impacts of implementing potable reuse in LBWD to the impacts of the current water source plan for 2025 has the potential to inform future policy decisions.

Creation of scenarios for case study. We used quantities the quantities of water that LBWD reported having used in 2010 in the LBWD Urban Water Management Plan[41] to establish baseline levels of imported water, groundwater, and recycled water for non-potable applications used by LBWD. In addition, we used the projected water use from different sources for LBWD in 2025 and 2035 that were reported in the LBWD Urban Water Management Plan (imported water, groundwater, recycled water for non-potable applications, and desalination) to create the reference water source scenario "Business as Usual" (BAU) for 2025 and 2035. According to LBWD plans, desalination is expected to provide 5,000 AF of water annually when introduced in 2025 and grow to 10,000 AF/year in 2035.[41] These BAU values were used as a starting point for

exploring three additional hypothetical water source scenarios (i.e., scenarios in which different percentages of water use from different sources would be implemented) for LBWD in 2025 and 2035. A description of the various water source mixes used in each of the scenarios is provided below and are summarized in **Table 3-1**. All of the scenarios projected for 2025 and 2035 at LBWD incorporate anticipated increases in demand due to population growth based on projections provided in the LBWD Urban Water Management Plan[41]. See **Appendix 1** for a description of the calculations that were performed to determine the potential supply of wastewater available for reclamation and treatment for either NPR or DPR in LBWD.

For Scenario 1 (S1): BAU, we used projections for water demand and water source utilization for 2025 and 2035 that were reported in LBWD's 2010 urban water management plan.[41] (**See Table 3-2.**) The BAU scenario assumes introduction of seawater desalination (5,000 AF of water annually in 2025 and 10,000 AF/year in 2035) to meet increased demand due to population growth.

In Scenario 2 (S2): "Mixed Reuse" (MIXED), we investigated how outcome variables (energy use, GHG emissions and cost) would change if LBWD used recycled water treated for both potable and non-potable reuse instead of imported water or seawater desalination. In this scenario (**Table 3-1**), we assumed that the projected demand would be the same as in the BAU scenario and that LBWD would use the same quantity of recycled water for non-potable reuse as in the BAU scenario from 2025 and 2035, but that no imported water or desalinated seawater would be used by LBWD in 2025 and 2035. We assumed that, instead of using imported water and desalinated water, LBWD would use recycled water that had been treated for DPR. LBWD

currently has the capacity to use additional recycled water from nearby Los Coyotes Water Reclamation Plant (LCWRP),[42,43] but would need to implement new infrastructure by 2025 to be able to treat this water for DPR. Currently only 28.6% of the treated wastewater generated from the LCWRP facility is used within the service area, and the remaining is discharged into the nearby San Gabriel River.[42,43]

In Scenario 3 (S3): "Maximizing Direct Potable Reuse" (POTABLE), we asked the question of how outcome variables (energy use, GHG emissions and cost) would change if LBWD maximized use of recycled water that is treated for potable reuse (via DPR) in 2025 and 2035. As was the case for Scenario 2, this scenario assumes that no imported water or desalinated seawater would be used. (**See Table 3-1**.) Scenario 3 differs from Scenario 2 in that all of the recycled water used by the LBWD in Scenario 3 would be treated for DPR, and no water would be treated for non-potable reuse. Like Scenario 2, Scenario 3 assumes that that LBWD would implement infrastructure improvements to treat water for DPR by 2025. To produce the required amount of water for DPR, LBWD would need to supplement their own treated water supply with treated water from an outside source (i.e., nearby LCWRP).[41-43] Scenario 3 allows us to explore whether costs to treat a larger quantity of recycled water to potable standards outweigh the associated costs of continuing to import water and building a seawater desalination facility or the costs associated with building dual-plumbed systems necessary to handle recycled water treated for non-potable reuse.

In Scenario 4 (S4), "Maximizing Desalination" (DESAL), we asked the question of what outcome variables (energy use, GHG emissions and cost) would change if LBWD maximized

use of seawater desalination in 2025 and 2035. As was the case for Scenario 2, this scenario assumes that no imported water would be used by LBWD by 2025 and that the quantity of groundwater and recycled water used for NPR in 2025 and 2035 would be the amounts that were projected by LBWD projected in their 2010 water management plan.[41] (See **Table 3-1**.) Scenario 4 differs from Scenario 2 in that it assumes that desalinated water is used instead of the recycled water for DPR that was assumed in Scenario 2. The purpose of this scenario is to demonstrate the impacts when a significant portion of water demand comes from seawater desalination. By contrast, in the BAU scenario, the amount of water coming from seawater desalination is low compared to imported water in 2025 and 2035. DESAL thus provides insights for decision makers into whether or not making significant investments in seawater desalination technology over current water source plans (i.e., continuing to import water) would be beneficial and also allows decision makers to directly compare the impacts of investing in a desalination facility to those of investing in a facility to recycle water for potable reuse.

Energy Demand Data and Estimates for LBWD Water Sources. Using an approach similar to that employed previously by Wilkinson,[44] energy demand was assessed for each component of the water system (i.e., extraction/collection, treatment, distribution/discharge) for each water source in LBWD, then added together to calculate total energy for that water source. We obtained energy demand data or demand estimates directly from water suppliers for LBWD (e.g., the energy demand for conveyance of imported water was obtained from the MWD). (See **Table 3-2**[45-50] and **Appendix 1**.)

Where energy demand data were not available for LBWD, we obtained estimates for energy demand by performing a regression analysis using equations and data obtained from the American Water Works Association Research Foundation (AwwaRF).[47] The AwwaRF had previously reported a data set for system parameters related to energy use for a national sample of water utilities and wastewater facilities.[47] This report contains data from 125 water utilities and 266 wastewater treatment plants in the United States, including 46 water utilities and 20 wastewater treatment plants from California (including LBWD).[47] The data in the AwwaRF report includes system parameters related to water utility and wastewater facilities' energy use, including number of groundwater sources and groundwater pumps, groundwater well depth, types of water treatment technology, size of population served, service area size, length of water mains, high and low area elevation, and other energy use factors for each of the water utilities and wastewater treatment plants they studied, as well as data on total energy use and energy use for production (groundwater extraction), treatment, and distribution.

Because LBWD participated in the AwwaRF survey, we had access to data for LBWD on size of the area served by the water district, the number of groundwater pumps used, and the total length of water mains for LBWD. We verified the accuracy of the LBWD data in the AwwaRF report with staff at LBWD.[51] Using formulae provided in the AwwaRF report, we conducted regression analyses to determine energy estimates for (1) "production" of groundwater in LBWD (i.e., groundwater extraction), (2) treatment of potable water for LBWD, and (3) distribution of potable water in LBWD, based on the area size, number of groundwater pumps, and length of water mains data available for LBWD. See **Appendix 1** for more details regarding how the regression analysis was performed and the equations used in that analysis.

Calculations of energy demand for 2025 and 2035 for each scenario for LBWD. To obtain energy demand estimates for each water use scenario for LBWD for 2025 and 2035 (**Table 3-3**), the estimates for the energy demand for each water source in LBWD (**Table 3-2**) were multiplied by projected water demand values (**Table 3-1).** See **Appendix 1** for more detailed information about where the energy demand numbers originated from, and why they were selected to use in this analysis.

GHG emissions calculations for LBWD water source scenarios. GHG emissions for of the water source scenarios in LBWD were calculated from energy demand using a multiplier reported by the SCE of 0.35kg CO_2 -eq/kWh [CO_2/kilowatt hour].[52] (**Table 3-2, Table 3-3.**)

Estimated unit costs used for LBWD case study. For water sources currently used by LBWD, baseline cost estimates was obtained from publicly available utility websites and reports,[43,53-58] or from LBWD through a public information request.[45,49,59] Data sources for cost for each water source used by LBWD are summarized in **Table 3-4**; estimated baseline costs for each water source used by LBWD are summarized in **Table 3-5**. Because LBWD does not currently use desalinated water, we used cost estimates obtained from the paper "A Perspective on Reverse Osmosis Water Desalination: Quest for Sustainability"[49] which includes summary values of best available cost data for existing reverse osmosis operations for seawater desalination. This paper was used to represent costs versus the costs of an existing facility because no two seawater desalination facilities are the same. Likewise, because LBWD does not currently have an advanced treatment facility (which would be required to treat reclaimed water to standards

required for potable reuse), we used data for complete advanced treatment of recycled water in Orange County Water District (OCWD). These data were obtained via publicly available reports and through public information request at OCWD.[45,57] Costs for OCWD were used as an estimate because OCWD is located in close proximity to LBWD and is likely to have similar factors that contribute to overall cost. See **Appendix 1** for more detailed information about where the estimates for unit cost for current and future water sources for LBWD originated from, and why they were selected for use in this analysis.

We also considered how costs for different water sources might change between 2010 and 2035. Imported water costs are projected to increase by 9% annually over the 25-year time horizon between 2010 and 2035, as a result of declining supplies and increasing conveyance costs.[53-56] **(Table 3-5)** Personal communications from staff at local water facilities suggest that costs for groundwater and recycled water for non-potable reuse are unlikely to change dramatically between 2010 and 2035. However, it might reasonably be assumed that, as a result of improvements in technology, costs for desalination and purification of recycled water for potable applications as a result of improvements in technology may decrease between baseline and 2035.

Cost calculations for water source scenarios in LBWD case study. For each water source scenario, costs were calculated by summing the product of the projected quantity of water used from each source in that scenario (**Table 3-1**) and the range of prices per AF for that source (**Table 3-5**):

$$Y_t = \sum_{x=0}^{n} Q_{xt} P_{xt}$$

Where Y_t is total expenditures in year t,

n is the number of water sources,

Q_{xt} is the quantity in AF of water source x in year t, and

P_{xt} is the price per AF of water for water source x in year t.

We calculated three possible expected expenditures for each scenario: a "low" cost (Y_{t-low}), using the low end of the cost range for each source (P_{xt-low}), a "high" cost (Y_{t-high}), using the high end of the cost range for each source ($P_{xt-high}$), and a "medium" cost ($Y_{t-medium}$), using the median cost of the range for each source ($P_{xt-medium}$). The resulting low, medium, and high cost estimates from each scenario are provided in **Table 3-6**.

RESULTS AND DISCUSSION

Water source scenarios used to explore impacts of water source choices for Long Beach Water District.

To explore how water source choices impact health, we developed four different scenarios for water source use for our case study, LBWD, for 2025 and 2035.

Scenario 1 (S1) "Business as Usual" (BAU) reflects the current water source mix proposed for 2025 and 2035 in LBWD's 2010 urban water management plan.[41] This scenario assumes that LBWD will continue to rely on imported water, groundwater, and non-potable reuse, and will start to use a small amount of seawater desalination (5,000 AF in 2025 and 10,000 AF in 2035).

Scenario 2 (S2) "Mixed Reuse" (MIXED) was designed to explore what the impacts would be of replacing both imported and desalinated water with recycled water treated for potable reuse.

Scenario 3 (S3) "Maximizing Potable Reuse" (POTABLE) was designed to explore the impacts of replacing imported, desalinated water, *and* recycled water treated for non-potable reuse with recycled water treated for potable reuse.

Scenario 4 (S4), "Maximizing Desalination" (DESAL) was designed to explore the impacts of replacing both imported and recycled water treated for non-potable reuse with desalinated water (and not treating any recycled water for potable reuse).

Summary of qualitative factors that have impacted water source choices and how they related to water sources in the LBWD case study.

Our literature review identified four factors that have traditionally guided decisions about water source choices (**Figures 3-1, 3-2**):

- Sustainability
- Technical feasibility
- Water quality
- Public perception

Subsequently, we provide an assessment of how each of these factors as they pertain to water sourcing decisions at LBWD.

Sustainability of LBWD water sources and implications for LBWD water sources. Sustainability of water sources is a particularly critical issue in Southern California because California has

highly variable annual precipitation[29] and because the population of California is already high and expected to grow from 37 to 60 million people (a 162% increase) by 2050.[60]

The sustainability of LBWD's water sources varies greatly. Reliance on imported water in California is threatened by increased temperatures, which result in more precipitation as rain instead of snow.[29] Traditionally, seasonal snowpack has been relied upon to store freshwater until the warmer and drier months, though increased temperatures during winter can prevent adequate storage and capture for later use.[29] Groundwater sources rely on local precipitation to recharge. Without reliable and consistent precipitation, groundwater supplies are shrinking.[34] Conversely, recycled water treated for non-potable or DPR, and seawater desalination are more sustainable water sources since their sources (e.g., treated wastewater and seawater) are not affected by weather patterns. Although health-related impacts may be associated with recycled waters or seawater desalination, these sources are largely exempt from sustainability issues.

Water quality of LBWD water sources and implications for LBWD water sources. Water quality indicators include measurements of turbidity, coliform bacteria, lead, and arsenic, amongst other potential contaminants.[61,62] Imported water at LBWD is provided by the MWD; this water is tested for over 100 potential contaminants daily by both MWD and LBWD, and meets or exceeds federal and state water quality standards.[61,62] MWD and LBWD publish detailed water quality reports annually that include water quality parameters for water sources used by the water district.[61] The Los Angeles Sanitation Department controls LBWD's recycled water treated for non-potable reuse, which meets tertiary water treatment standards.[43]

LBWD's groundwater is extracted from Southern California's Water Replenishment District (WRD) Central Basin. The groundwater quality within WRD's Central Basin currently meets all federal and state water quality standards.[63] However, some restricted areas of the basin have poorer quality and are unsuitable for potable use; therefore, they are not incorporated within WRD's groundwater extraction. WRD closely monitors the entire basin for more than 100 water quality constituents through daily sampling of its well network to ensure emerging water quality concerns are identified and managed quickly.[63] WRD also monitors the basin for salinity levels to ensure no seawater intrudes into the groundwater basin.[63]

For sources not currently utilized at LBWD (e.g., seawater desalination and potable water via DPR), data from established facilities (i.e., Carlsbad's Poseidon seawater desalination plant operated by San Diego County Water Authority, or Complete Advanced treatment technology at OCWD) were reviewed. San Diego County Water Authority (SDCWA) controls the water quality of water generated via seawater desalination at the Poseidon plant. Water generated via seawater desalination is blended with established imported water sources, which meets state and federal water quality criteria. Similar to LBWD, water quality indicators include measurements of turbidity, coliform bacteria, lead, and arsenic, amongst other potential contaminants. Our literature review did not reveal any significant water quality concerns specific to desalinated water.

The OCWD treats recycled water for potable reuse using technology known as advanced water treatment (AWT) within their drinking water treatment facility.[64] The AWT process at OCWD involves microfiltration, reverse osmosis, and oxidation and disinfection via ultraviolet light

treatment before the treated water can be introduced into the potable water supply. Once OCWD's treated water is blended with potable water, it is held to the same potable water quality standards as water from other sources. Although OCWD treats recycled water for IPR, the same technology could be used to treat DPR.[64] For recycled water treated for potable reuse (direct or indirect), current treatment technologies exist and are constantly improving to best address any related health issues. In general, research reveals that recycled water generated from DPR does not pose any additional risk versus current, established water supplies.[3,6,9,10]

Technical feasibility of LBWD water sources and implications for LBWD water sources. Technical feasibility for LBWD water sources refers to not only available technology to introduce a new water source, but also whether or not the existing infrastructure and location are available and practical. Technical feasibility has downstream impacts on health because without the appropriate foundation to implement a water source, the health benefits or harms described herein cannot be realized.

Although LBWD does not currently operate a seawater desalination facility, a facility recently opened nearby in Carlsbad, California, thus proving its feasibility. In Long Beach, the city is situated along the coast, rendering a seawater desalination plant feasible because of the convenient access to seawater.[41,65] Although barriers may exist regarding the feasibility and expansion of seawater desalination facilities persists, public opposition to high overall costs of developing seawater desalination facilities and the environmental impacts to coastal habitats and marine life may prevent facilities from breaking ground.[66,67]

Likewise, although LBWD does not currently treat recycled water for potable reuse, this technology is available in neighboring Orange County and LBWD already has some of the infrastructure required.[22,64,68,69]. Existing facilities are in place at LBWD to treat wastewater for non-potable applications; over 2014-2015, LBWD treated 14.59 Million Gallons/day (MGD), or 16350 AF/year at their 25 MGD facility.[43] Although facilities exist to treat water for non-potable uses, capabilities to treat wastewater for *potable reuse* do not exist at LBWD. Additionally, LBWD would need to increase the volume of wastewater to support the potable water needs of their population. A potential method to increase LBWD's wastewater would be to reroute water from a neighboring facility, such as the LCWRP. Capabilities for producing recycled water for potable reuse currently exist in Southern California, but require greater infrastructure and space than is currently available at LBWD; neighboring OCWD produces recycled water treated for potable reuse via IPR reuse via their Groundwater Replenishment System.[70] IPR is not feasible for LBWD because unlike OCWD, LBWD does not operate or have rights to their own groundwater basin; LBWD purchases its groundwater from WRD's Central Groundwater Basin in Southern California. Alternatively, DPR requires less physical space than IPR and is likely to be integrated into California's water supply in the near future. At the end of 2016, California's State Water Resources Control Board (SWRCB) released a report[71] describing the feasibility for developing regulations to support recycled water treated for DPR as drinking water source in the near future.

Public perception of LBWD water sources. Public perception of health risks related to water sources has been shown to shape their public acceptance and is particularly a concern for proposed new sources of water, particularly use of recycled water for DPR. Currently, public

opposition is considered to be the greatest obstacle to successful implementation DPR in California.[3,6,22,64,68,69] Not surprisingly, the most common public concerns from DPR surround water quality and the safety of the water supply.

Public education and outreach campaigns may help address public concerns about quality and safety of recycled water. Among the many factors shaping public perceptions and acceptability, information from trusted sources has been shown to be key.[16,17,25,26] An example in San Diego demonstrated that greater focus on public education campaigns can lead to greater public acceptance. In the 1990s, plans to build a recycled water facility for non-potable reuse in San Diego were derailed due to lack of public support.[17,25,26] Years later, after a strong public education and outreach effort, San Diego was able to boost public support for recycled water from 26% in 2004 to 79% by 2012; when the public is not informed or supportive, it is difficult for decision makers to act on substantial changes to local water sources.[16,17,25,26]

Expansion of recycled water is not the only new source subject to public criticism. In response to new seawater desalination facilities in Southern California, environmental groups have publicly raised concerns over the environmental impacts to sea life, marine habitats, and water pollution from increased brine discharge.[66,67]

Summary of implications of quantitative factors for the water scenarios in the LBWD case study.

In addition to these qualitative factors, we also identified three quantitative factors that have traditionally guided decisions about water source choices (**Figures 3-1, 3-2**):

- Energy demands
- GHG emissions, and
- Cost of water sources.

Subsequently, we report our assessment of three factors for the water sources scenarios in the LBWD case study.

Energy and GHG emissions for LBWD water scenarios. We estimated energy demand for the current and projected water sources for LBWD (**Table 3-2**) and used these estimates to calculate total energy demand for the four urban water source scenarios we modeled for LBWD for both 2025 and 2035 (**Table 3-3**) as well as to calculate the estimated GHG emissions for each of the water sources and scenarios (**Tables 3-2, Table 3-3**).

These results indicate that scenarios which include increased recycled water use—both for potable and non-potable uses—have a considerably lower energy and GHG emission footprint compared to the BAU scenario (i.e., the water use mix currently planned by LBWD) as soon as 2025. The highest predicted total energy demand and GHG emissions per year were those within the DESAL scenario (i.e., the scenario in which all imported and recycled water would be replaced with desalinated water). This assumes that current energy demands for desalination technology. Although the high end of the range has potential to improve in the future, the low range is unlikely to change significantly in the future. The next highest predicted total energy demand and GHG emissions per year were those for the BAU scenario. Energy demand and GHG for the BAU scenario are driven by high energy demand for imported water. The lowest projected total energy demand and GHG emissions were those for the MIXED scenario (i.e., the

scenario in which imported water and desalinated water would be replaced with recycled water treated for potable reuse) and the POTABLE scenario (i.e., the scenario in which imported water, desalinated water, *and* recycled water treated for non-potable reuse would be replaced with recycled water treated for potable reuse).

Cost estimates for LBWD water scenarios. The estimated unit price for each of the current and potential water sources LBWD (**Table 3-5**) was used to develop low, medium, and high cost projections for each scenario in LBWD case study for 2025 and 2035 compared to Baseline (2010; **Table 3-6**).

These results of this analysis (**Table 3-6, Figure 3-3**) indicate that scenarios that include a significant expansion of recycled water use—for either potable or non-potable uses—have the potential to cost LBWD significantly less than either the BAU scenario (LBWD's current plan) or the DESAL scenario (maximizing use of desalinated water) as early as 2025. Comparison of the high end of the projections for each of the four water use scenarios reveals that the highest projected costs were associated with the BAU scenario. Within the low range of cost projections, the order of cost for the different scenarios was DESAL <MIXED < POTABLE <BAU. Though for medium and high cost projections, the cost range changes to MIXED <POTABLE <DESAL <BAU. Notably, the *highest* estimates for the MIXED and POTABLE scenarios (in which imported and desalinated water is replaced with recycled water treated for potable reuse) is lower than the *lowest* estimate for the BAU scenario (i.e., what LBWD currently plans to use) in 2025 and the medium estimates for DESAL. The highest single cost contribution to the BAU costs comes from imported water, reflecting a projected increase in the cost of imported water of 9-

10% annually during the study period (**Tables 3-8, 3-9**).[53-56] Despite the variety of factors contributing to desalination facilities (local permit and regulation costs, intake and discharge costs, feed water quality costs, finished water quality costs, project delivery mechanism costs, and associated infrastructure and operations costs (power, proximity, labor, etc.)), future costs for desalination facilities are trending downward, whereas imported water supplies are becoming more expensive; this was observed in the lowest estimate for DESAL, which is lower than the low estimates for MIXED and POTABLE.[49] The downtrend in overall seawater desalination costs is generally associated with improved Seawater Reverse Osmosis (SWRO) membrane performance and advances in energy recovery from the desalination process which could be implemented at a potential new facility at LBWD.[49,50] See **Table 3-9** for description of uncertainty in costs for Imported Water and Seawater Desalination.

Downstream health impacts related to water source decisions and the implications for LBWD water source scenarios.

We developed a logic framework[72] that illustrates the causal pathways with the potential to result in downstream health-related impacts from water source decisions; this framework can systematically assess potential health impacts and guide potential water source decisions (**Figure 3-2**). The primary pathways are related to sustainability of water sources, technical feasibility, water quality, public perception, energy demand, GHG emissions, and costs. Subsequently, we illustrate how this framework can be used to assess the health impacts of water sources and water source scenarios for LBWD. The potential health risks and benefits of each of the water source scenarios that we explored for LBWD are summarized in **Table 3-7**.

Causal pathways that link sustainability of water sources to health: implications for LBWD water sources and scenarios. A myriad of health-related issues are tied to reliance on unsustainable water sources. Water scarcity often compromises nutrition as a result of diminished agricultural production,[32] or can result in diminished water quality from salt-water intrusion or decreases in groundwater basin water levels.[34,73,74] Secondary health impacts from water scarcity include respiratory and cardiovascular disease (e.g., from air quality issues arising from dust from dry lake beds), as well as financial stressors that lead to poor health (e.g., stress, heart disease, exacerbation of illnesses) and morbidity and mortality related to insufficient or unclean water.[32,36,37,75]

Water scarcity will also have implications for California's green spaces,[76] which play a valuable role in mediating health.[77] Reduced water for irrigating green spaces combined with temperature increases has the potential to result in more frequent extreme heat events and urban heat island effects.[78] Green space is an important mediator for the onset of climate change, which can prevent health impacts related to heat stroke, respiratory disease, activity-related health impacts (obesity, heart disease), and mental and elderly health issues.[77,79-84]

The two water sources for LBWD that are most affected by water scarcity are imported water and groundwater. LBWD purchases imported water from the MWD,[41] which sources that water from the State Water Project (i.e., from Northern California's the Sacramento and San Joaquin Rivers).[13] The primary source of these rivers is snow melt from the Sierra Nevada Mountains. Historically, precipitation in these ranges is highly variable; to combat this variability, the State of California has implemented a series of reservoirs for storing water.[13] However, during

extended droughts, such as that experienced from 2011-2017, these reservoirs can run low, resulting in water scarcity.[29,85] Global and local models suggest that climate change will result in droughts in the American Southwest that are increasingly severe and last for increasingly long periods of time.[29] As a result, imported water used by LBWD, which is already vulnerable to water scarcity, is projected to become even more vulnerable.[29,85] Groundwater supplies are more vulnerable because replenishment rates are slow compared to the rate of use.[34] The high use of impervious surfaces throughout the Southern California basin and diversion of run-off to concrete-lined "rivers" that deliver rain water into the ocean have further slowed natural replenishment rates for the region.[13] In addition, groundwater reservoirs are vulnerable to sea water intrusion resulting from sea level rise associated with global climate change.[63]

As a result of these differential vulnerabilities, the water source scenarios for LBWD that are most dependent on imported water are those in which we would expect to see the greatest negative of the health impacts associated with water scarcity. Because all of the scenarios rely equally on groundwater, the vulnerability of LBWD groundwater to water scarcity does not vary between the scenarios. By contrast, only one of the scenarios we explored, the BAU scenario (i.e., the water mix proposed by LBWD for 2025 and 2035 in their 2010 urban water management plan[41]) relies on imported water. As a result, switching to any of the other three scenarios (MIXED, POTABLE, and DESAL) would decrease the region's vulnerability to the negative health impacts associated with water scarcity.

Causal pathways that link energy requirements and GHG emissions to health: implications for LBWD water sources and scenarios. Substantial energy is necessary for moving and treating

water across California (i.e., imported water).[12,47,86-90] Most of this energy comes from the combustion of fossil fuels, which release air pollutants and GHGs into the atmosphere.[47] Because GHG emissions drive global climate change, they are indicators for negative health impacts both globally and locally.[11,12,32] Globally and locally, climate change is projected to cause temperature increases, water scarcity, and increased extreme weather events that will affect energy use, and how changes in energy use have potential to affect health.[32,91] For example, increases in temperatures have potential to exacerbate air quality concerns stemming from GHG emissions.[32,91] Poor air quality conditions are shown to be associated with increased rates of respiratory disease and cardiopulmonary and lung cancers, especially over long periods of exposure.[92,93]

The water sources for LBWD that have the highest energy demand and GHG emissions are imported water and desalinated water, and hence the scenarios that depend on these sources have the highest health risks related to climate change and air quality. Scenarios at LBWD that require the highest energy demand and GHG emissions are BAU and DESAL, as importing water across California and generating desalinated seawater are highly energy intensive. Choosing to follow implement either scenarios will exacerbate the health impacts of climate change from energy and GHG emissions, whereas choosing to implement a less energy intensive option (MIXED, POTABLE) may mitigate these effects.

Causal pathways that link water costs to health: implications for LBWD water sources and scenarios. Higher costs for water have the potential to result in downstream impacts on health through reduced access to healthy foods, reduced access to health-related services, and possibly

increases in stress-related mental health impacts, all mediated by household financial strain.[36,37,94-96] These impacts are anticipated to be greatest on low income communities, because a greater portion of monthly budgets of low-income households are allocated toward utilities and are already more financially strained.[36,94]

The water source for LBWD that we anticipate would have the biggest impacts on health through this pathway is imported water. Of the current and projected water sources for LBWD that were examined herein, imported water was the most costly (**Table 3-5**). Imported water is costly because imported water is so energy intensive; increasing energy costs are projected to increase the costs of imported water by 9-10% annually during the period we modeled (**Table 3-9**).[54-56] In addition to imported water, depending on the local needs of the facility, seawater desalination has potential to be costly both because of energy intensity and also because of operations and management fees related to bring new facilities online.[97-99] Desalination facilities vary between locations, thus there is a wide range of cost uncertainty based on local needs and conditions (**Table 3-9**).[48,50,97-99] Alternatively, implementation of a facility to generate potable water via DPR would require minimal infrastructure changes to existing facilities and thus would not contribute as much to the cost burden as desalinated seawater or imported water.[22,45,64]

As a result of these factors, the two scenarios for LBWD that we anticipate would have the biggest differential negative impacts on health through this pathway is BAU; this scenario relies on the costliest water source (imported water). Implementing BAU versus MIXED or POTABLE would disproportionately burden low-income or already vulnerable populations through increased utility prices.[94] For lowest income populations, amount of monthly income spent on

housing, utilities, and health care costs accounts for nearly 50% of the budget. In contrast, in higher income households, the amount of monthly income spent on housing, utilities, and health care costs accounts for 40% of the budget.[94] Changes in water costs and availability will impact lower income households more since these households are already more financially strained and since a greater portion of their water use is for basic needs, with little leeway for cuts in water use without impacting quality of life.[94]

Causal pathways that link water quality to health: implications for LBWD water sources and scenarios. Water quality has long been the standard criterion that decision makers consider when evaluating the health impacts of water source decisions. Water quality has the power to impact health through potential water contaminants or constituents, which may cause sickness,[3,6] and meeting established water quality standards is a high priority for water districts at all times.[41] In most situations in developed countries, water quality is unlikely to be a concern for existing water sources (e.g., imported water, groundwater), although the introduction of a new potable water source involves new parameters for measurement. Climate change has potential to change the water quality of different water sources. For example, during drought, less precipitation results in less groundwater basin recharge. The lack of precipitation can result in less dilution of potential contaminants in the groundwater basin, leading to poorer water quality.[34,73,74] For imported water sources from Northern California, decreased freshwater availability risks increasing salinity in the water supply, thus rendering the source unfit to drink.[29,30]

Potable water generated via DPR that is not treated to the appropriate level has the potential to pose health risks.[19,100] Some constituents, such as microbial pathogens and viruses, have the

potential to affect human health, depending on their concentration and routes of exposure.[19,20] Pathogens are of particular concern because of their acute human health effects; viruses require special attention because of their low infectious dose and small size.[19,22-24] Current treatment technologies exist and are constantly improving to best address any related health issues, though in general, research reveals that recycled water generated for DPR does not pose any additional risk versus current, established water supplies.[3,6,9,10]

Among the water sources assessed for the LBWD case study, DPR poses the greatest potential risk related to water quality. However, research suggests that DPR, as it would likely be implemented in California, could minimize these water quality risks and keep within current standards and on par with other water sources. Nonetheless, educating the public and generating positive public perception related to DPR would be vital for successful implementation of DPR in LBWD.[14-16,18] The scenarios that include implementing recycled water treated for DPR, and are hence the most affected by this constraint are the MIXED and POTABLE scenarios. By contrast, water quality concerns for BAU and DESAL are minimal within LBWD.

LIMITATIONS

The limitations of this study fall into two main categories:

- Limitations in the data available for the LBWD case study and resulting in uncertainty of the calculations for energy demand, GHG emissions, and cost; and
- Limitations in the ability to generalize the results obtained for the case study to other locations.

Limitations in the data available for the LBWD case study and resulting in uncertainty of the calculations for energy demand, GHG emissions, and cost.

Where energy demand estimates for LBWD were unavailable, we determined energy demand estimates through regression analysis based on a data set collected by the AwwaRF, which surveyed the energy demand water districts in California and New York. (**See Table 3-1, Appendix 1**)[47] Limitations include the uncertainty of future energy sources, development of new technology with lower overall energy demand, and the energy demand of new sources if they were to be implemented at LBWD's facilities. To better represent the energy demand of water districts beyond these areas, a research priority would be to conduct surveys in other regions across the country.

Estimated GHG emissions for LBWD water sources were calculated from the energy demand estimates. The GHG emissions data is reliant on an effect parameter, a multiplier developed by SCE, which reflects the amount of CO_2 released per kilowatt-hour energy expended.[52] The value reported by the SCE assumes that all energy demands are met using electricity from the grid and that all of this electricity is generated through combustion of fossil fuels. If, for example, all energy to move water in California were powered by solar energy, or the energy the amount of GHG released from energy demand would change dramatically.

The costs for different water sources have the potential to change in the future, with increasing energy costs, new energy sources, new technology development, and changes in drought conditions. Cost data is based on established ranges of LBWD-specific water sources; data were obtained directly from the entity distributing the water to LBWD. Limitations lie in the

uncertainties about these new water sources, including uncertainties about whether these water sources would be powered using electricity from the grid. In addition, the future costs of both imported water and groundwater will be highly dependent upon future drought and precipitation patterns, which are hard to predict. In addition, the future cost of imported water will be highly dependent on energy costs, which we have assumed will increase by 9% annually, but are fairly uncertain. Likewise, the costs for building and implementing either a seawater desalination facility or a facility for treated water for DPR are uncertain and depend both on the pace of technology development for these treatment modalities over the next 5-10 years and site-specific costs for LBWD. A full evaluation of the latter was beyond the scope of this study.

Limitations related to generalizing the results obtained for the case study to other locations. The ability of other jurisdictions to generalize from the results obtained for the LBWD case study are limited due to variations in climate, geography, quality of local water sources, local regulations, and public perception from one region of the world to another. Differences in current climate and projected impacts of climate change on precipitation patterns vary dramatically from one region of the world to another and have important implications for costs and sustainability of local water sources. Likewise, local geography (e.g., proximity to abundant surface water sources, proximity to the ocean, etc.) can have a dramatic impact on the costs and sustainability of local water sources and the feasibility of implementing new sources, including desalinated water. The quality of water sources is also highly variable across the globe. Local regulations and perceptions about recycled water impact the feasibility of implementing DPR. In California, the development DPR regulations were mandated by the SWRCB in Fall of 2016 and are still in development. Developing regulations to allow for DPR will expedite the feasibility of these

types of facilities outside California and beyond. As water scarcity and droughts increase in frequency and severity worldwide, perception of new water sources (including recycled water for DPR and desalinated water) are likely to shift dramatically, but these shifts are likely to vary considerably from one region to another.

As a result of this high level of variability in a wide range of critical factors, we do not recommend that other water districts take the results reported herein for LBWD and assume that they apply to their own jurisdictions. However, the framework and methodology that we reported herein should be generally applicable to other water districts, assuming that they have access to comparable data and estimates for key values related to energy use and cost for different water sources as well as information about the quality and sustainability of their local water sources and a reasonable understanding of any factors (e.g., geography, local infrastructure, climate, regulations, and public perception) that will influence their water source options.

CONCLUSION

A full consideration of the health issues associated with different long-term water source decisions can help provide a more complete basis for making evidence-based decisions. Here, we present a framework that lays out the most important pathways by which water source decisions impact health. These pathways include:

- Sustainability,
- Technical feasibility,
- Water quality,
- Public perception,

- Energy demand,
- GHG emissions, and
- Costs.

We developed a framework to explore how different water management choices in that community would likely impact health. Specifically, we focused on LBWD and investigated four different water source scenarios:

- *Scenario 1 (S1) "Business as Usual"* (BAU), the current water source mix proposed for 2025 and 2035 in LBWD's 2010 urban water management plan;[41]
- *Scenario 2 (S2) "Mixed Reuse" (MIXED)*, where both imported and desalinated water from the current plan are replaced with recycled water treated for potable reuse;
- *Scenario 3 (S3) "Maximizing Potable Reuse" (POTABLE)* where imported, desalinated water, *and* recycled water treated for non-potable reuse specified in the current plan are replaced with recycled water treated for potable reuse; and
- *Scenario 4 (S4), "Maximizing Desalination" (DESAL)* where imported and recycled water treated for non-potable reuse in the current plan are both replaced with desalinated water.

This analysis revealed that, while each of the scenarios has different possible benefits and risks, that overall, those scenarios that would increase use of recycled water (MIXED and POTABLE) have a greater potential to benefit public health.

Even without considering development of new technologies going forward, the overall energy and GHG emissions associated with implementing DPR have the potential to be lower than available sources. DPR could be achieved by increasing the capacity at LBWD's existing water

treatment facilities and adding advanced treatment capabilities. The neighboring OCWD provides evidence of the technical feasibility for recycling water for potable reuse, and proves the potential for achieving water quality suitable for DPR. Additionally, using wastewater as a source has the potential to be more sustainable than relying solely on imported water or groundwater, which have greater reliance on precipitation patterns. The overall financial burden of implementing DPR may not be not as high in the future as the existing option of relying on existing, unreliable unsustainable sources (e.g., imported water). DPR may also be financially subsidized by future state or federal government grants to help offset the burden at local water districts. Public education and outreach campaigns regarding DPR processes are a good place to begin.

REFERENCES FOR CHAPTER 3

1. California State Water Resources Control Board. The California Water Boards' annual performance report - 2010: Water recycling-water reclamation. http://www.waterboards.ca.gov/about_us/performance_report_1011/plan_assess/12512_ww_recycling.shtml. Published 2010.
2. Sutula MA, Lyons GS. 2011 SCCWRP Annual report: Effluent discharges to the Southern California Bight from large municipal wastewater treatment facilities from 2005 to 2009. Southern California Coastal Water Research Project. http://ftp.sccwrp.org/pub/download/DOCUMENTS/AnnualReports/2011AnnualReport/ar11_223_236.pdf. Published 2011.
3. National Resources Council of the National Academies. *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater.* 2012.
4. CH2M Hill. *Tampa Water Resource Recovery Project Pilot Studies.* Tampa, Florida: CH2M Hill;1993.
5. Lauer WC, Rogers SE. The Demonstration of Direct Potable Reuse: Denver's Pioneer Project. *American Water Works Association/Water Education Foundation Proceedings.* 1996:269-289.
6. National Resources Council of the National Academies. Issues in potable reuse: The viability of augmenting drinking water supplies with reclaimed water. Washington DC National Academies Press 1998.
7. Bull R, Crook J, Whittaker M, Cotruvo J. Therapeutic dose as the point of departure in assessing potential health hazards from drugs in municipal wastewater. *Regul Toxicol Pharm.* 2011;60(1):1-19.

8. Rodriguez C, Cook A, Van Buyner P, Devine B, Weinstein P. Screening health risk assessment of micropollutants for indirect potable reuse schemes: A three tiered approach. *Water Sci Technol.* 2007;56(11):35-42.

9. Snyder S, Benotti M, Rosario-Ortiz F, Vanderford B, Drewes JE, Dickenson E. *Comparison of chemical composition of reclaimed and conventional waters final report.* Alexandria, VA: WateReuse Foundation; 2010.

10. Snyder S, Trenholm R, Snyder M, Bruce GM, Pleus RC, Hemming JD. *Toxicological relevance of EDCs and pharmaceuticals in drinking water.* Denver, CO: American Water Works Association Research Foundation; 2008.

11. Cole BL, Sokolow S. Public health impacts of urban water conservation in California: opportunities to maximize co-benefits and minimize harm with case-study analysis of water conservation in the city of Burbank. Prepared by the UCLA Fielding School of Public Health's Health Impact Assessment Project in collaboration with The Los Angeles County Department of Public Health http://www.ph.ucla.edu/hs/health-impact/reports.htm. Published 2014.

12. Sokolow S, Godwin H, Cole BL. Impacts of urban water conservation strategies on energy, greenhouse gas emissions, and health: Southern California as a case study. *Am J Public Health.* 2016;106(5).

13. Green D. *Managing Water: Avoiding Crisis in California* Los Angeles: University of California Press; 2007.

14. Hurlimann A, Dolnicar S. Public acceptance and perceptions of alternative water sources: A comparative study in nine locations. *Int J Water Resour D.* 2016;32(4):650-673.

15. Hartley T. Public perception and participation in water reuse. *Desalination.* 2005;187(1-3):115-126.

16. Bridgeman J. Public perception towards water recycling in California. *Water Environ J.* 2004;18(3):150-154.

17. Garcia-Cuerva L, Berglund EZ, Binder AR. Public perceptions of water shortages, conservation behaviors and support for water reuse in the United States. *Resour Conserv Recy.* 2016;113:106-115.

18. Ross VL, Fielding KS, Louis WR. Social trust, risk perceptions and public acceptance of recycled water: Testing a social-psychological model. *J Environ Manage.* 2014;137:61-68.

19. Asano T, Burton FL, Leverenz HL, Tsuchihashi R, Tchobanoglous G. *Water Reuse: Issues, Technologies and Applications.* New York: McGraw-Hill; 2007.

20. Craun M, Craun G, Calderon R, Beach M. Waterborne outbreaks reported in the United States. *J Water Health.* 2006;4(2):19-30.

21. Rodriguez C, Weinstein P, Cook A, Devine B, Van Buyner P. A proposed approach for the assessment of chemicals in indirect potable reuse schemes. *J Toxicol Envl Health.* 2007;70(19):1654-1663.

22. Raucher R, Tchobanoglous G. The opportunities and economics of direct potable reuse. WateReuse Foundation: https://www.watereuse.org/product/14-08-1. Published 2014.

23. Tanaka H, Asano T, Schroeder ED, Tchobanoglous G. Estimating the safety of wastewater reclamation and reuse using enteric virus monitoring data. *Water Environ Res.* 1998;70(1):39-51.

24. Orange County Water District. *Technical Memorandum on Microbial Water Quality.* Supplemental Report to the NWRI Groundwater Replenishment System Independent Advisory Panel; 2010.

25. Ormerod KJ, Scott CA. Drinking wastewater: Public trust in potable water. *Sci Technol Hum Val.* 2013;38(3):351-373.

26. Water Education Foundation. *Layperson's Guide to Water Recycling.* 2013.

27. Lozier JC, Kitis M, Kim JH, Mi B, Marinas BJ. Evaluation of Biologic and Nonbiologic Methods for Assessing Virus Removal By and Integrity of Pressure Membrane Systems. *In KJ Howe Edition: Membrane Treatment for Drinking Water & Reuse Applications: A Compendium of Peer Reviewed Papers*. Denver, CO: American Water Works Association; 2006:399-420.

28. United States Census Bureau. California quick facts. http://quickfacts.census.gov/qfd/states/06000.html. Published 2010.

29. California Department of Water Resources. Managing an uncertain future: Climate change adaptation strategies for California's Water. http://www.water.ca.gov/climatechange/docs/ClimateChangeWhitePaper.pdf. Published October 2008.

30. Hanak E, Lund J. *Adapting California's Water Management to Climate Change.* San Francisco, CA: Public Policy Institute of California 2008.

31. MacDonald G. Water, Climate Change, and Sustainability in the Southwest. *P Natl Acad Sci USA*. 2010;107(50).

32. Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. Impact of regional climate change on human health. *Nature.* 2005;438(7066):310-317.

33. Vorosmarty CJ, Green P, Salisbury J, Lammers RB. Global water resources: Vulnerability from climate change and population growth. *Science.* 2000;289(5477):284-288.

34. California Department of Water Resources. Public update for drought response: groundwater basins with potential water shortages and gaps in groundwater monitoring. http://www.water.ca.gov/waterconditions/docs/Drought_Response-Groundwater_Basins_April30_Final_BC.pdf. Published April 2014.

35. Gleick PH, Pacific Institute. Dirty water: estimated deaths from water-related diseases 2000-2020. http://www.pacinst.org/wp-content/uploads/sites/21/2013/02/water_related_deaths_report3.pdf. Published February 2002.

36. Wilkinson R. *Unhealthy Society: The Affliction of Inequality.* London: Routledge; 1997.

37. McDonough P, Duncan, GJ, Williams, D, House, J. Income dynamics and adult mortality in the United States, 1972-1989. *Am J Public Health* 1997;87(1476-83).

38. Cole B, Shimkhada, R, Fielding, JE, Kominski G, Morgenstern, H. Methodologies for realizing the potential of health impact assessment. *Am J Prev Med.* 2005;28(4):382-389.

39. Cole B, Wilhelm M, Long P, Fielding J, Kominski G. Prospects for Health Impact Assessment in the United States: New and Improved Environmental Impact Assessment or Something Different? *J Health Polit Polic.* 2004;29(6):1153-1186.

40. Committee on HIA, Board on Environmental Studies and Toxicology, Division on Earth and Life Sciences NRC. *Improving Health in the United States: The Role of Health Impact Assessment.* Washington DC: National Academy of Sciences; 2011.

41. Long Beach Water District. Long Beach Water District urban water management plan. http://www.lbwater.org/2010-urban-water-management-plan. Published 2010.

42. Los Angeles County Sanitation District. Los Coyotes Water Reclamation Plant. http://www.lacsd.org/wastewater/wwfacilities/joint_outfall_system_wrp/los_coyotes.asp. Published 2016.

43. Sanitation Districts of Los Angeles County. Twenty-Sixth annual status report on recycled water use: Fiscal year 2014-2015. http://www.lacsd.org/civicax/filebank/blobdload.aspx?blobid=12648. Published 2016.

44. Wilkinson R. Analysis of the energy intensity of water supplies for West Basin Municipal Water District. http://www.westbasin.org/files/general-pdfs/Energy--UCSB-energy-study.pdf. Published March 2007.

45. Hunt W. Orange County Water District Public Records Request: Costs and Energy Demand of Complete Advanced Treatment. 2016. Email.

46. Scott J. Metropolitan Water District Request for Information: Conveyance Energy to Southern California. 2016. Email.

47. AWWA Research Foundation (AwwaRF); California Energy Commission; New York State Energy Research and Development Authority. *Energy Index Development for Benchmarking Water and Wastewater Utilities.* Denver, CO; 2007.

48. Hartling E. Energy Demand of Wastewater Treatment Process at Los Angeles County Sanitation District. 2016. Email.

49. Cohen Y, Semiat R, Rahardianto A. A Perspective on Reverse Osmosis Water Desalination: Quest for Sustainability. *AlChE J.* 2017;63(6):1771-1784.

50. Rao P, Aghajanzadeh A, Sheaffer P, Morrow W, et al. Volume 1: Survey of available information in support of the energy-water bandwidth study of desalination systems. Lawrence Berkeley National Laboratory. https://eetd.lbl.gov/sites/all/files/lbnl-1006424.pdf. Published 2016.

51. Monzon D. Long Beach Water District survey data. 2016. Email.

52. Southern California Edison. 2012 corporate responsibility & sustainability. https://www.sce.com/wps/wcm/connect/68145014-2eba-40c2-8587-6482ce056977/CRR_08202013.pdf?MOD=AJPERES&ContentCache=NONE. Published 2012.

53. Metropolitan Water District. Historical water rates. http://mwdh2o.com/PDF_Who_We_Are/Historical_Water_Rates.pdf. Published 2016.

54. Metropolitan Water District. FY 2014-15 and FY 2015-16 budget and CY 2015-2016 rates and charges. http://mwdh2o.com/WhoWeAre/Management/Financial-Information/Pages/default.aspx. Published 2016

55. Sforza T. Imported water prices: Up 96 percent since 2006. *Orange County Register*. http://www.ocregister.com/taxdollars/strong-478683-water-mwd.html. Published 2012.

56. Sforza T. Water rates double in 8 years: Are you getting soaked? *Orange County Register*: http://www.ocregister.com/taxdollars/strong-478657-water-percent.html. Published 2012.

57. Burris DL. *Groundwater Replenishment System 2009 Annual Report.* Fountain Valley, CA: Prepared for the California Regional Water Quality Control Board Santa Ana Region; 2010.

58. City of San Diego. *San Diego Recycled Water Study (Final Draft).* San Diego, CA: City of San Diego; 2012.

59. Weatherly K. Groundwater Costs at Long Beach Water District. 2016. Email.

60. State of California Department of Finance. Interim population projections for California and its counties 2010-2050. http://www.dof.ca.gov/research/demographic/projections/2012. Published 2012.

61. Long Beach Water District. Water quality report 2015. http://www.lbwater.org/sites/default/files/documents/LBWD CCR 2015 Updated.pdf. Published 2016.

62. Metropolitan Water Districts of Southern California. Annual drinking water quality report http://www.mwdh2o.com/PDF_About_Your_Water/2.3.1_Annual_Water_Quality_Report.pdf. Published 2016.

63. Water Replenishment District of Southern California. Regional groundwater monitoring report water year 2015-2016: Central and West Coast Basins Los Angeles County. http://www.wrd.org/sites/pr/files/2015-16 RGWMR Final.pdf. Published 2017.

64. Tchobanoglous G, Cotruvo J, Crook J, et al. *Framework for Direct Potable Reuse.* WateReuse Foundation, American Water Works Association, Water Environment Foundation, National Water Research Institute; 2015.

65. Long Beach Water District. Desalination and water purification research and development report no. 158: Two pass nanofiltration seawater desalination prototype testing and evaluation. http://www.usbr.gov/research/AWT/reportpdfs/report158.pdf: U.S. Department of the Interior Bureau or Reclamation. Published 2013.

66. Cavanaugh K. Desalination isn't the answer to California's water problem. *Los Angeles Times*: http://articles.latimes.com/2013/nov/2013/news/la-ol-ocean-water-desalination-20131112. Published November 2013.

67. Sierra Club Los Angeles Chapter. Coastal Commission to weigh desalination plan opposed by Sierra Club. http://angeles.sierraclub.org/news/blog/2013/04/coastal_commission_weigh_desalination_plan_opposed_sierra_club. Published 2013.

68. Leverenz H, Tchobanoglous G, Asano T. Direct Potable Reuse: A Future Imperative. *J Water Reuse Desal.* 2011;1(1):2-10.

69. Tchobanoglous G, Leverenz H, Nellor M, Crook J. *Direct Potable Reuse: A Path Forward.* WateReuse Research Foundation; 2011.

70. Orange County Groundwater Replenishment System. Groundwater replenishment system technical brochure. http://www.gwrsystem.com/. Published 2015.

71. State Water Resources Control Board. Investigation on the feasibility of developing uniform water recycling criteria for direct potable reuse: Report to the legislature in compliance with Water Code Section 13563. http://www.waterboards.ca.gov/publications_forms/publications/legislative/docs/2016/dpr_report.pdf. Published 2016.

72. UCLA Health Impact Assessment Clearinghouse Learning & Information Center. Logic frameworks. http://www.hiaguide.org/methods-resources/methods/logic-frameworks. Published 2017.

73. Asano T, Cotruvo JA. Groundwater recharge with reclaimed municipal wastewater: Health and regulatory considerations. *Water Res.* 2004;38(8):1941-1951.

74. National Resources Defense Council. *California's Contaminated Groundwater: Is the State Minding the Store?* 2001.

75. Gleick PH; Pacific Institute. *Dirty Water: Estimated Deaths from Water-Related Diseases 2000-2020.*

76. Herriman J, White S, Campbell D, Institute for Sustainable Futures and ACIL Tasman. Review of water restrictions volume 1: Review and analysis. Final report for National Water Commission of Australia. http://archive.nwc.gov.au/__data/assets/pdf_file/0019/11755/Water_restrictions_Volume_1.pdf. Published 2009.

77. Maas J, Verheij, RA, Groenewegen, PP, de Vries, S, Spreeuwenberg, P. Green space, urbanity, and health: How strong is the relation? *J Epidemiol Commun H.* 2006;60(7):587-592.

78. McPherson E, Simpson, JR, Peper PJ, Xiao, Q; Center for Urban Forest Research USDA Forest Service. Benefit-cost analysis of Santa Monica's municipal forest. http://www.fs.fed.us/psw/programs/uesd/uep/products/cufr47_SMonicaBCA.pdf. Published November 2001.

79. Wilby R. Constructing climate change scenarios of urban heat island intensity and air quality. *Environ Plann B.* 2008;35(5):902-919.

80. Basu R, Samet, J. Relation between elevated ambient temperature and mortality: A review of the epidemiologic evidence. *Epidemiol Rev.* 2002;24:190-202.

81. Gladwell V, Brown, DK, Wood, C, Sandercock, GR, Barton, JL. The great outdoors: How a green exercise environment can benefit all. *J Extreme Physiol Med*. 2013;2(3).

82. Kuo F, Taylor, FE. A potential natural treatment for attention deficit/hyperactivity disorder: Evidence from a natural study. *Am J Public Health.* 2004;94(9):1580.

83. Nowak D, Crane, DE, Stevens, JC. Air pollution removal by urban trees and shrubs in the United States. *Urban For Urban Gree.* 2006;4:115-123.

84. Jennings V, Gaither, CJ. Approaching environmental health disparities and green spaces: An ecosystem services perspective. *Int J Environ Res Public Health.* 2015;12(2):1952-1968.

85. California Department of Water Resources; State of California; The Resources Agency. Preparing for California's next drought: Changes since 1987-1992. http://www.water.ca.gov/waterconditions/drought/docs/Drought_Report_87-92.pdf. Published 2000.

86. Wolff GW, Cohen R, Nelson B, Natural Resources Defense Council. Energy down the drain: The hidden costs of California's water supply. https://www.nrdc.org/water/conservation/edrain/edrain.pdf. Published 2004.

87. California Energy Commission. California's Water -- Energy Relationship (Final Staff Report). *Prepared in Support of the 2005 Energy Policy Report Proceeding (04-IEPR-01E).* 2005.

88. Bates M. *Energy Use in California Wholesale Water Operations: Development and Application of a General Energy Post-Processor for California Water Management Models*. Davis, CA: Civil and Environmental Engineering, UC Davis; 2010.

89. California Energy Commission. Final staff report, California's water-energy relationship, CEC-700-2005-011-SF. http://www.energy.ca.gov/2005publications/cec-700-2005-011/cec-700-2005-011-sf.pdf. Published November 2005.

90. California Energy Commission, Navigant Consulting Inc. *Refining Estimates of Water-Related Energy Use in California.* PIER Final Project Report (CEC-500-2006-118); 2006.

91. Intergovernmental Panel on Climate Change. Climate change 2013: The physical science basis. https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WGIAR5_SPM_brochure_en.pdf. Published 2013.

92. Pope III CA, Burnett RT, Thun MJ, et al. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA.* 2002;287(9):1132-1141.

93. Dockery DW, Pope CA, Xu X, et al. An association between air pollution and mortality in six U.S. Cities. *New Engl J Med.* 1993;329(24):1753-1759.

94. California Budget Project. Making ends meet: How much does it cost to raise a family in California? http://calbudgetcenter.org/wp-content/uploads/131212_Making_Ends_Meet.pdf. Published 2013.

95. Siefert K, Heflin CM, Corcoran ME, Williams DR. Food insufficiency and the physical and mental health of low-income women. *J Women Health.* 2001;32(1-2).

96. Vozoris NT, Tarasuk VS. Household food insufficiency is associated with poorer health. *J Nutr.* 2003;133(1):120-126.

97. Barnes M. Why South Bay environmentalists oppose West Basin's planned ocean water desalination plant. *The Daily Breeze* http://www.dailybreeze.com/environment-and-nature/20160722/why-south-bay-environmentalists-oppose-west-basins-planned-ocean-water-desalination-plant. Published July 2016.

98. Cooley H, Heberger, M; Pacific Institute. Key issues for seawater desalination in California: Energy and greenhouse gas emissions. http://pacinst.org/wp-content/uploads/sites/21/2013/05/desal-energy-ghg-full-report.pdf. Published 2013.

99. Wittholz MK, O'Neill BK, Colby CB, Lewis D. Estimating the cost of desalination plants using a cost database. *Desalination.* 2008;229(1):10-20.

100. Craun GF. Causes of waterborne outbreaks in the United States. *Water Sci Technol.* 1991;24:17-20.

101. Cooley H, Christian-Smith J, Gleick P. *California's Next Million Acre-Feet: Saving Water, Energy and Money.* Oakland, CA: Pacific Institute; 2010.

102. Gleick P. *Waste Not, Want Not: The Potential for Urban Water Conservation in California.* Oakland: Pacific Institute; 2003.

103. Gleick PH. Water in crisis: Paths to sustainable water use. *Ecol Appl.* 1998;8(3):571-579.

104. Lior N. Sustainability as the quantitative norm for water desalination impacts. *Desalination.* 2017;401:99-111.

105. Weeks J. Groundwater Replenishment Fee at Water Replenishment District. 2016. Email.

106. Seawater Desalination in the San Diego Region [press release]. 2016.

107. Hartley TW. Public perception and participation in water reuse. *Desalination.* 2006;187(1–3):115-126.

108. Dolnicar S, Hurlimann A, Grun B. What affects public acceptance of recycled and desalinated water? *J Water Res.* 2011;45(2):933-943.

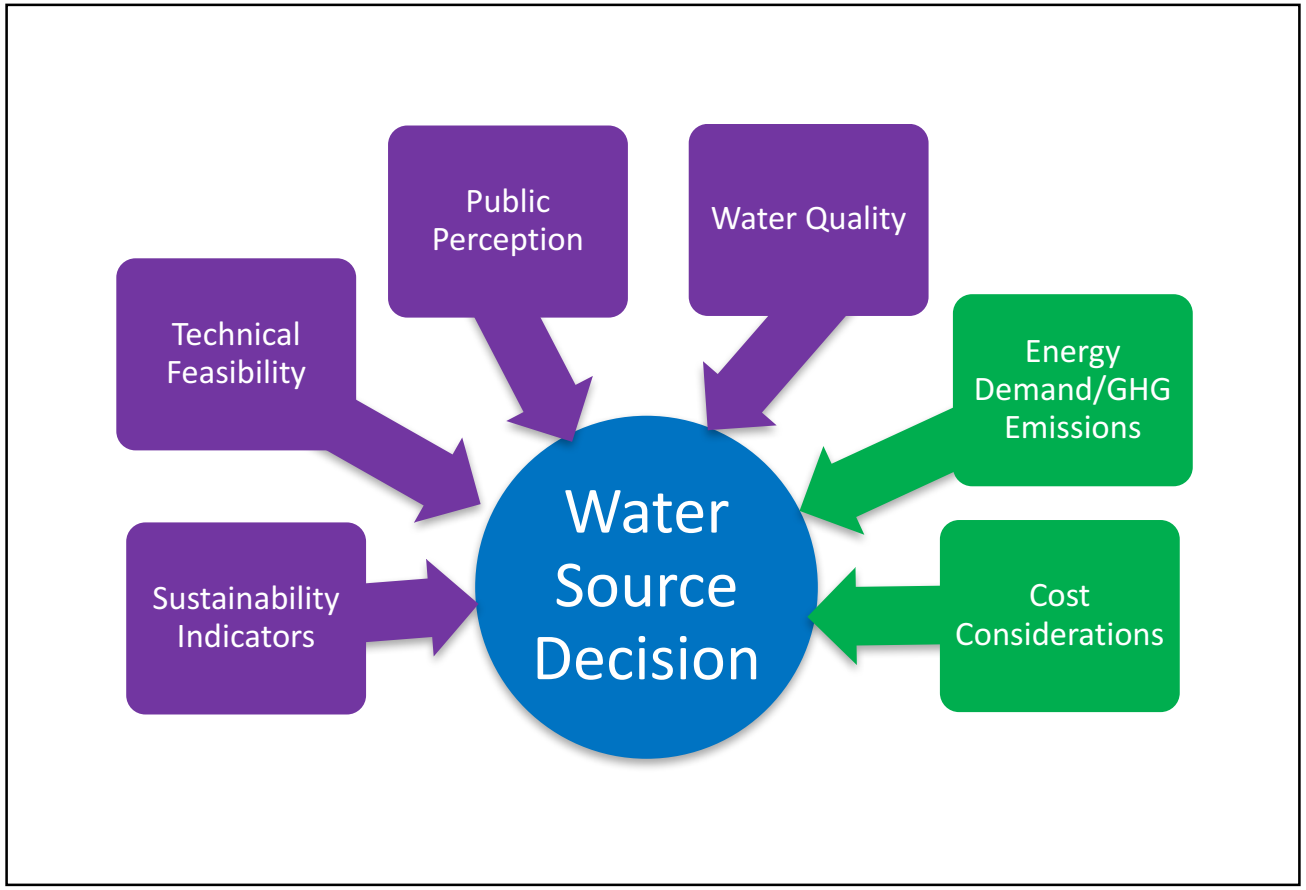

Figure 3-1: Factors that have traditionally been considered when making water source decisions. Factors in purple represent those amenable to evaluation via qualitative analysis; factors in green represent those amenable to evaluation via quantitative analysis.

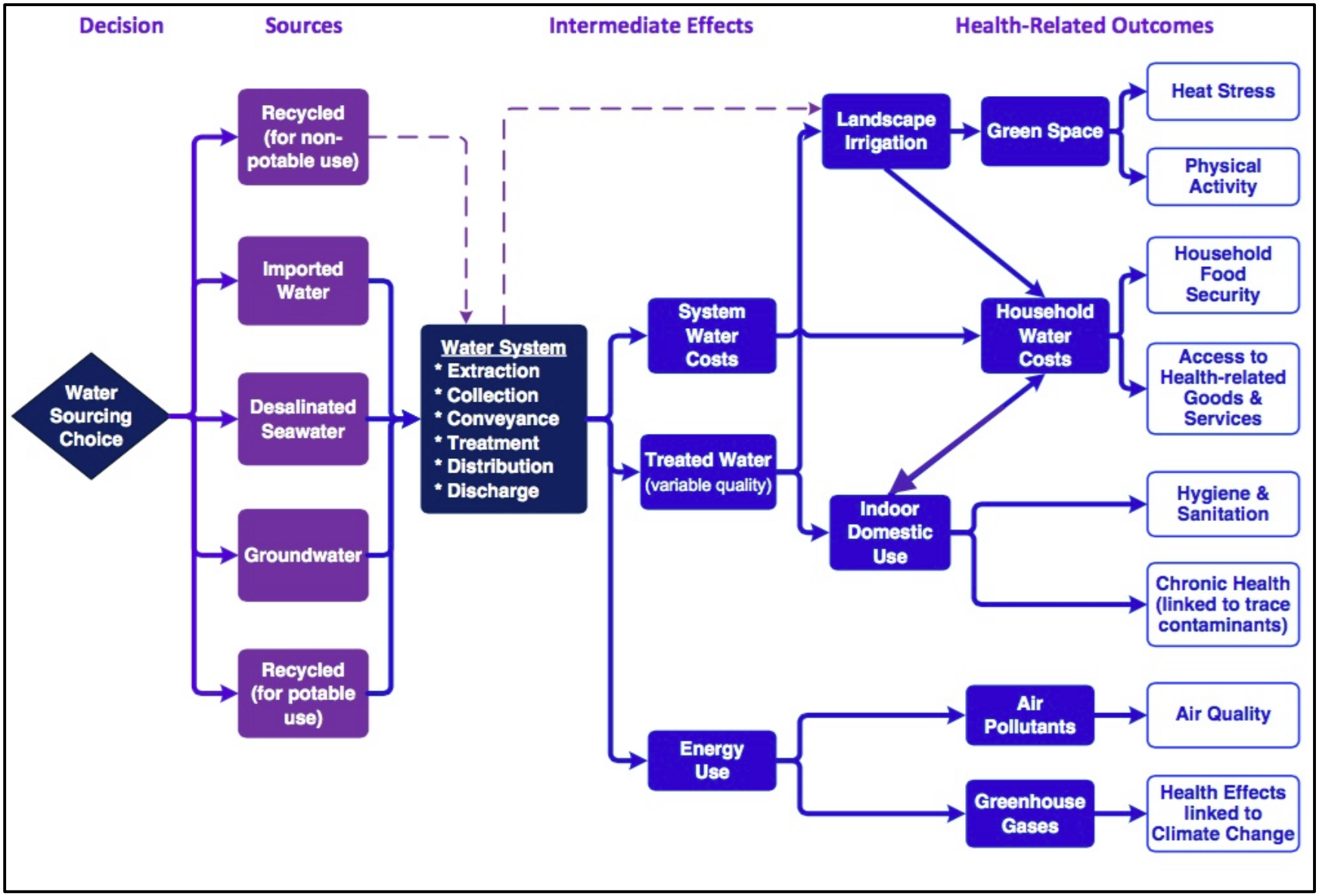

Figure 3-2: Logic framework of water source decision making and the potential for downstream health-related impacts.

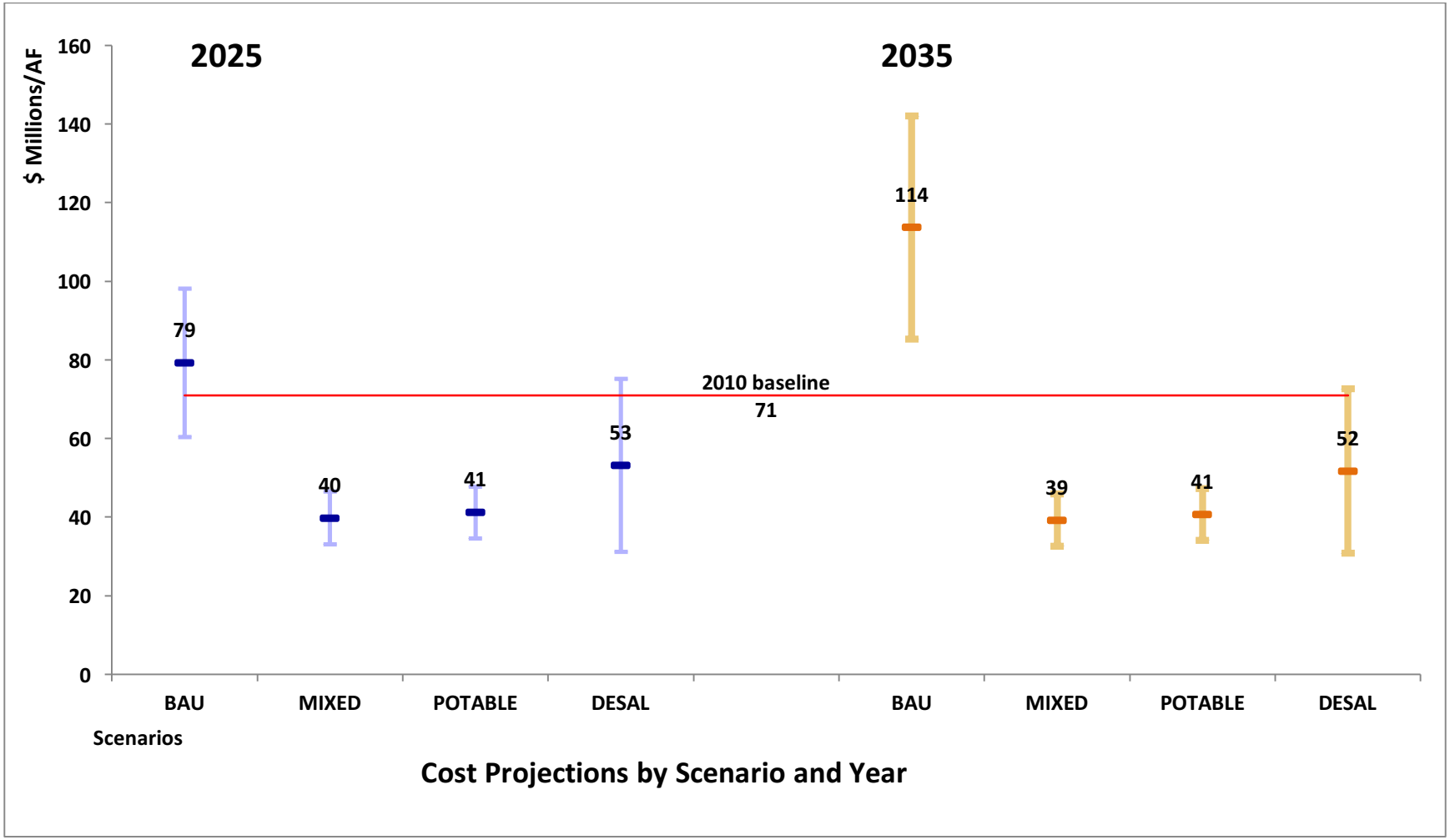

Figure 3-3: Projected costs of each water source scenario for LBWD in 2025 and 2035 compared to baseline (2010). Costs projections for each scenario are shown for 2025 (blue) & 2035 (yellow), with 2010 baseline costs represented by the horizontal red line. Error bars represent high and low cost projections for each scenario, with the horizontal bars (dark blue and green) showing the "medium" cost projections (i.e., those produced when median projected costs per water source was used); the numbers above these bars provide the medium cost projections for each scenario in millions of dollars.

Table 3-1: Projected amount of water from each source assumed for each scenario in Long Beach Water District case study developed herein

	Amount of Water from Each Source Assumed in Each Scenario (AF/yr) for Years Specified								
Water Source	**Baseline[a]**	**S1: Business As Usual (BAU)[b]**		**S2: Mixed Reuse (MIXED)[c]**		**S3: Maximizing Potable Reuse (POTABLE)[d]**		**S4: Maximizing Desalination (DESAL)[e]**	
	2010	**2025**	**2035**	**2025**	**2035**	**2025**	**2035**	**2025**	**2035**
Imported	22,237	18,551	11,929	0	0	0	0	0	0
Groundwater	34,655	34,000	35,000	34,000	35,000	34,000	35,000	34,000	35,000
NPR	6,556	13,400	14,000	13,400	14,000	0	0	13,400	14,000
DPR	0	0	0	23,551	21,929	36,951	35,929	0	0
Desalination	0	5,000	10,000	0	0	0	0	23,551	21,929
TOTAL DEMAND	63,448	70,951	70,929	70,951	70,929	70,951	70,929	70,951	70,929

Note. NPR=Non-potable Reuse, DPR=Direct Potable Reuse. All scenarios rely on water demand data from Long Beach Water District's 2010 Urban Water Management Plan.[41] For more details about how the water demand calculations were conducted, please see **Appendix 1**.

[a] Baseline includes actual water demand values for LBWD in 2010.

[b] For Scenario 1 "Business as Usual," includes projected water demand for LBWD in 2025 and 2035.

[c] For Scenario 2 "Increasing Reuse," LBWD water demand projections in 2025 and 2035 were altered to include recycled water for both potable and non-potable uses and eliminate imported and desalinated water.

[d] For Scenario 3 "Maximizing Potable Reuse," LBWD water demand projections in 2025 and 2035 were altered to maximize recycled water for potable reuse and eliminate imported and desalinated water.

[e] For Scenario 4 "Maximizing Desalination," LBWD water demand projections in 2025 and 2035 were altered to maximize recycled water for potable reuse and eliminate imported and desalinated water.

Table 3-2: Estimated current energy demand for components of current and potential water sources used by Long Beach Water District (LBWD) and total estimated energy demand for LBWD water sources.

	Estimated Energy Demand for Components of Water Sources for LBWD				Estimated Total Energy Demand for Water Sources for LBWD (kWh/AF)
	Extraction/Collection (kWh/AF)	**Conveyance** (kWh/AF)	**Treatment** (kWh/AF)	**Distribution/ Discharge** (kWh/AF)	
Imported Water	n/a	2910[c] (2580-3240)[c]	40[a]	<10[a]	**2630-3290**
Groundwater	90[a]	<10[a]	40[a]	<10[a]	**140-160**
Non-Potable Reuse	30[b] (20-40)[b]	n/a	450[b] (400-500)[b]	<10[a]	**410-490**
Direct Potable Reuse	30[b] (20-40)[b]	n/a	1300 (1270-1575)[b]	<10[a]	**1260-1340**
Seawater Desalination	n/a	n/a	3700-9250[d,e]	<10[a]	**4670-4690**

[a]Energy demand values estimated using regression analysis (see Methods and Reference 47) were estimated to have an uncertainty of ± 10 kWh/AF.

[b]Personal correspondence from staff at LA County Sanitation District; see reference 48.

[c]Personal correspondence from staff at Metropolitan Water District; see reference 46.

[d]Range provided reflects energy demand reported for total specific energy consumption for the seawater desalination process; see reference 49.

[e]Note: The theoretical minimum energy consumption at 50% recovery for seawater desalination using a single stage RO with 100% efficient pump and energy recovery is estimated to be ~1950 kWh/AF. This number was obtained from reference 49.

Table 3-3: Estimated energy demand and greenhouse gases emitted for each water source scenario for Long Beach Water District in 2025 and 2035 compared to baseline (2010)

		Amount of Energy Required (Million kWh-AF/year) and GHG Released (Million kg CO2-AF/year) for Each Scenario for LBWD at Specific Years								
		Baseline[a]	S1: Business As Usual (BAU)[b]		S2: Mixed Reuse (MIXED)[c]		S3: Maximizing Potable Reuse (POTABLE)[d]		S4: Maximizing Desalination (DESAL)[2]	
		2010	2025	2035	2025	2035	2025	2035	2025	2035
Recycled	**Energy**	3-4	6-7	6-8	37-45	35-43	48-60	47-58	6-7	6-8
	GHG	1-1.2	2-3	2-3	13-16	12-15	17-21	16-21	2-3	2-3
Imported	**Energy**	52-73	44-61	31-39	0	0	0	0	0	0
	GHG	18-26	15-21	11-14	0	0	0	0	0	0
Desal.	**Energy**	n/a	19-46	37-93	0	0	0	0	97-140	90-130
	GHG	n/a	6-16	13-32	0	0	0	0	34-49	31-46
Total	**Energy**	60-82	19-46	79-145	41-51	40-49	53-65	52-64	98-230	92-216
	GHG	21-29	26-42	28-50	15-18	14-17	19-23	18-22	34-80	32-76

Note. Rows provide energy demand contribution of recycled water, imported, desalinated water and total energy required. All scenarios rely on water demand from Long Beach Water District's 2010 Urban Water Management Plan [41]. Recycled= Recycled water for both non-potable and potable uses. Desal= Seawater Desalination. Imported= Imported water. Total=Amount from all water sources within scenario (ex: imported, groundwater, seawater desalination, recycled water for potable and non-potable reuse)

[a] Baseline includes actual water demand values for LBWD in; energy and greenhouse gas emissions were calculated using LBWD-specific data given baseline water demand.

[b] For Scenario 1 "Business as Usual," includes projected water demand for LBWD in 2025 and 2035; energy and greenhouse gas emissions were calculated using LBWD-specific data given Scenario 1 water demand.

[c] For Scenario 2 "Increasing Reuse," LBWD water demand projections in 2025 and 2035 were altered to include recycled water for both potable and non-potable uses and eliminate imported water and seawater desalination; energy and greenhouse gas emissions were calculated using LBWD-specific data given Scenario 2 water demand.

[d] For Scenario 3 "Maximizing Potable Reuse," LBWD water demand projections in 2025 and 2035 were altered to maximize recycled water for potable reuse and eliminate imported water and seawater desalination; energy and greenhouse gas emissions were calculated using LBWD-specific data given Scenario 3 water demand.
[e] For Scenario 4 "Maximizing Desalination," LBWD water demand projections in 2025 and 2035 were altered to maximize recycled water for potable reuse and eliminate imported water and seawater desalination; energy and greenhouse gas emissions were calculated using LBWD-specific data given Scenario 4 water demand.

Table 3-4: Data sources for each water source for Long Beach Water District case study

	Water Sources for Long Beach Water District				
	Imported	**Groundwater**	**Seawater Desalination**	**Non-potable Reuse**	**Direct Potable Reuse**
Water Quality Data	Long Beach Water District 2015 Water Quality Report[61]	Long Beach Water District 2015 Water Quality Report[61]	A Perspective on Reverse Osmosis Water Desalination: Quest for Sustainability[49]	Los Angeles Sanitation District 2014-2015 Status Report[43]	Orange County Sanitation District reports[24,70]
Sustainability Considerations Data	Determined through the peer-reviewed literature, agency reports and grey literature.[29-31,85,101-104]				
Greenhouse Gas Emissions Data	Used 0.35 kg CO2/kWh, the California-specific Greenhouse Gas Emissions multiplier.[52] GHG for each water source was calculated based on total energy per source.				
Cost Data	Metropolitan Water District Public Information Request[46]	Long Beach Water District Public Information Request/Water Replenishment District[59,105]	A Perspective on Reverse Osmosis Water Desalination: Quest for Sustainability[49,106]	Los Angeles Sanitation District 2014-2015 Status Report[43]	Orange County Water District Public Information Request[45]
Technical Feasibility Data	This source is already established at LBWD.[41]	This source is already established at LBWD.[41]	Technical feasibility is based on LBWD's 2014 seawater desalination report.[41,65]	This source is already established at LBWD.[41,43]	Technical feasibility was determined by industry-specific technical reports[22,64] and through conversations with experts.
Public Perception Data	Public perception for all sources was determined through a combination of peer-reviewed literature and through conversations with experts.[14,16-18,29,85,107,108]				

Table 3-5: Estimated unit price (in dollars per AF) for current and potential water sources Long Beach Water District used in calculations

	Cost Per Acre-Foot ($/AF)				
	Imported	**Groundwater**	**Non-Potable Reuse**	**Direct Potable Reuse**	**Seawater Desalination**
Baseline	850-1300[53-56]	257-426[59]	585-805[43]	700-900[45]	654-2122[49]

Table 3-6: Low, medium and high cost projections for each Scenario in Long Beach Water District case study for 2025 and 2035 compared to Baseline (2010)

Projection	Cost Projections ($M/AF-year) for Each Scenario								
	Baseline	S1: Business As Usual		S2: Mixed Reuse		S3: Maximizing Potable Reuse		S4: Maximizing Desalination	
	2010	2025	2035	2025	2035	2025	2035	2025	2035
Low	26	60	85	33	33	34	34	31	30
Medium	33	79	114	40	39	41	41	53	52
High	68	98	142	46	46	48	47	75	73

Note. Costs in million dollars per acre-foot per year.

Table 3-7: Summary of key differences in the health impacts and other considerations that influence water source selection for Long Beach Water District water source scenarios

Scenario	1. Business As Usual • Imported Water (26%) • Groundwater (48%) • Non-potable Reuse 19%) • Seawater Desalination (7%)	2. Mixed Reuse • Groundwater (48%) • Non-potable Reuse (19%) • Direct Potable Reuse (33%)	3. Maximizing Potable Reuse • Groundwater (48%) • Direct Potable Reuse (52%)	4. Maximizing Desalination • Groundwater (48%) • Non-potable Reuse (19%) • Seawater Desalination (33%)
Relative Health Risks	• High health risks associated with climate change due to high GHG emissions; • High health risks associated with air quality due to high energy use; • Highest risk of food insecurity and diminished access to services due highest costs;	• Minimal risk to hygiene and sanitation from DPR. • Minimal risk resulting from trace contaminants in water treated for DPR.	• Minimal risk to hygiene and sanitation from DPR; • Minimal risk resulting from trace contaminants in water treated for DPR.	• Highest health risks associated with climate change due to highest GHG emissions; • Highest health risks associated with air quality due to highest energy use; • High risk of food insecurity and diminished access to services due high costs.
Relative Health Benefits	• Currently, quality of water sources is high.	• Lowest health risks associated with climate change and air quality; • Reduced heat stress and increased physical activity because recycled water available for landscape irrigation.	• Low health risks associated with climate change and air quality; • Reduced heat stress and increased physical activity because recycled water available for landscape irrigation.	• Little to no water quality concerns.

Scenario	1. Business As Usual • Imported Water (26%) • Groundwater (48%) • Non-potable Reuse 19%) • Seawater Desalination (7%)	2. Mixed Reuse • Groundwater (48%) • Non-potable Reuse (19%) • Direct Potable Reuse (33%)	3. Maximizing Potable Reuse • Groundwater (48%) • Direct Potable Reuse (52%)	4. Maximizing Desalination • Groundwater (48%) • Non-potable Reuse (19%) • Seawater Desalination (33%)
Other Considerations	• Existing sources have high public acceptance; • Future concerns related to insecurity of imported water. • Significant infrastructure needs.	• Public perception is a potential barrier; • Water sources are highly sustainable; • Minimal infrastructure additions needed to existing facilities.	• Public perception is a potential barrier; • Water sources are highly sustainable; • Minimal infrastructure additions needed to existing facilities.	• Local environmental concerns are a major barrier. • Water sources are highly sustainable; • Significant infrastructure needs.

Note. Water source percentages shown for each scenario are for 2025 estimates.

Table 3-8: Identification of the water source that contributes the most to cost for each scenario in the Long Beach Water District case study in 2025 and 2035 compared to baseline (2010)

Projection	Water Source that Contributes the Most to Cost in Each Scenario								
	Baseline	S1: Business As Usual		S2: Mixed Reuse		S3: Maximizing Potable Reuse		S4: Maximizing Desalination	
	2010	2025	2035	2025	2035	2025	2035	2025	2035
Low	GW	Imported	Imported	DPR	DPR	DPR	DPR	Desal	Desal
Medium	GW	Imported	Imported	DPR	DPR	DPR	DPR	Desal	Desal
High	GW	Imported	Imported	DPR	DPR	DPR	DPR	Desal	Desal

Note. Ground=groundwater; Imported=imported water; DPR=recycled water treated for direct potable reuse; Desal=desalination.

Table 3-9. Factors driving uncertainty in costs and energy for imported water and seawater desalination at LBWD.

Water Source	Main Factors Driving Uncertainty	
	Energy	**Cost**
Imported Water	- Relatively little uncertainty in energy demand.	MWD reports a range of current costs for imported water that includes year-to-year variation in: - Tiered water rate - System access rate - System power rate - Water stewardship rate - Treatment surcharge - Readiness to serve charge In addition there is uncertainty in the rate of escalation for cost of imported water, which depends on: - Infrastructure repair costs - Rising energy costs - Rising treatment costs
Seawater Desalination	- Treatment type - Presence of energy recovery - Seawater intake type - Conveyance to drinking water treatment facility	Price of seawater desalination varies by facility: - Local regulations & permitting costs - Intake and discharge costs - Feed water quality costs - Infrastructure and location costs - Project delivery mechanism costs - Infrastructure operations costs (power, proximity, labor).

CHAPTER 4

Perspectives on the Barriers Towards the Future of Recycled Water in California: Results from Interviews with Key Stakeholders

ABSTRACT

Expanded use of recycled water has the potential to improve the sustainability of water systems in areas with high levels of water insecurity, including California. Despite recent studies suggesting that expanded use of recycled water could be both beneficial to health and cost effective, the rates of recycled water use in California remain low. To identify barriers to expansion of recycled water use in California, we conducted open-ended interviews with a targeted sample of 12 key stakeholders who represent a range of viewpoints within California's recycled water community, including experts from government regulatory and public health agencies, wastewater suppliers, and independent consultants and engineers. Barriers identified by the respondents were related to the regulatory environment, infrastructure and funding, requirements for new technology, health risks, and public perceptions. Respondents provided concrete suggestions regarding how to lower these barriers and insights into the roles that public health professionals could play in this effort. This work suggests that public health professionals can play a critical role in facilitating the expanded use of recycled water and improving water security and sustainability worldwide.

INTRODUCTION

Recycling water is increasingly recognized as a valuable strategy for improving the resiliency of urban water supply systems,[1-3] but is relatively underutilized in most regions of the world. California offers an instructive case study for identifying barriers to recycled water use as well as approaches to lowering those barriers.[2,4] While in the midst of an extreme drought, California's conditions are anticipated to worsen both as the population grows,[5] and as climate change causes more frequent and severe water shortages.[6] Currently, California's South Coast basin (Los Angeles and surrounding areas) uses relatively little recycled water—just 11% of the basin's total water supply came from recycled water in 2009—even though the state is experiencing extreme drought, and will likely face greater water insecurity in the future.[7,8] In addition, most of the urban recycled water currently used in California is allocated toward non-potable applications, such as green space irrigation or seawater intrusion barriers.[8]

Going forward, use of recycled water for potable applications is likely to become increasingly important.[2,9,10] Potable reuse of recycled water, which involves treatment of wastewater to drinking water quality standards, is typically divided into two categories: DPR and IPR.[1] DPR refers to treated wastewater that is directly introduced into the potable water supply after treatment. By contrast, IPR refers to treated wastewater that is introduced into an environmental buffer (e.g., groundwater or a river) following treatment and before entering the potable water supply. (See **Figure 4-1**.) IPR has expanded in recent years across the world, particularly in areas suffering from extreme water scarcity (e.g., Singapore[11]). In California, many wastewater treatment plants provide recycled water for non-potable uses (e.g., landscape irrigation), but only seven wastewater treatment plants provide recycled water through IPR.[12] Currently, only four

facilities in the world produce potable water via DPR and only two facilities are in the United States.[1] Both United States facilities are located in Texas, and neither is currently in operation.[1,2]

Positive public perception of recycled water is a driver toward successful implementation of recycled water programs. Studies suggest public acceptance is heavily tied to public accessibility of information regarding recycled water processes and systems.[13-17] Unsurprisingly, the public is more accepting of alternative water sources during times of crisis, which is relevant to California's current drought.[18,19] For example, in San Diego, lack of public support derailed a water reuse project in the 1990s. Years later, with a strong public education and outreach effort, San Diego was able to boost public support for recycled water from 26% in 2004 to 79% by 2012; when the public is not informed and/or supportive, it is very difficult for decision makers to act on substantial changes to local water sources.[15,20,21]

For potable reuse, public opposition is considered the greatest obstacle to successful projects,[14,18,20,22] where most common public concerns surrounded water quality and the safety of the water supply. For example, many associate recycled water with the moniker "toilet to tap" or subscribe to the "yuck" factor, deeming the water unclean or unhealthy.[23,24] Similarly to recycled water for non-potable reuse, public concerns for potable reuse mainly surround safety and reliability of water quality.[14,18,20,22] Research has shown that technology exists to treat water for potable reuse, and should not be cited as the limiting factor for expanding potable reuse.[1-4,25,26] However, in some studies, public trust in water quality stemmed from the public's trust in water managers and their ability to ensure the best possible water quality.[14,16,18]

Two critical question that arise regarding potential expansion of recycled water: (1) why, in the face of a need for more sustainable water sources, hasn't California more aggressively pursued expanded use of recycled water and (2) what can be done to facilitate increased use of recycled water in California—including for potable reuse—in the years to come? Here, our goal was to more completely explore perceived barriers to expansion of recycled water in California as well as to identify how those barriers might be lowered. With the understanding that water and health are intricately linked,[27,28] we sought to identify how health factors may play a role in barriers to recycled water expansion. To this end, we conducted interviews with policymakers and professionals in the state's water and public health communities and asked these respondents about their perspectives on recycled water, expansion of potable reuse, including DPR, perceived barriers to implementation, health-related impacts and what to expect in the future.

Here, we report the results from these interviews, including insights gained into how barriers to the expanded use of recycled water in California could be lowered. Based on the results of these interviews, we provide specific recommendations for the roles that public health professionals could play in lowering these barriers, and how public health professionals might partner with other sectors to reduce barriers to expanded use of recycled water not only in California, but also in other areas with high water demand and scarce supply.

METHODS

Literature review.

We evaluated peer-reviewed and gray literature to better understand the status of recycled water for potable and non-potable reuse and to identify barriers to expansion of recycled water that had

been identified previously in the literature. The literature reviews performed for **Chapters 2** and **3** were supplemented with literature searches through Google Scholar and Web of Science using search terms "health AND recycled water" "recycled water AND water quality" "water reuse AND health." Additional sources recommended by respondents participating in the interviews were also reviewed.[28]

Study sample.

We employed a systematic snowball sampling strategy to identify professionals at government regulatory agencies, staff members of state and local public health departments, independent engineers and consultants, employees of local wastewater treatment facilities, and policy experts within the water community in California who had expertise in recycled water.[29] Initial contacts were established through the authors' participation in regional water management working groups, or through connections made while working with experts in the field. Our initial wave of interviews targeted stakeholders with expertise in areas related to barriers to expansion of recycled water in California that were identified during our literature review (i.e., regulatory expertise, technological expertise, and expertise in public perception). Through our initial interviews, we identified additional barriers to expansion (i.e., those related to infrastructure, funding, and health), which guided the selection of additional respondents with expertise in these areas (i.e., infrastructure, funding, and health). A third set of interviews was conducted to assure adequate representation from all sectors associated with recycled water use and barrier themes identified in the literature review and first two sets of interviews.

Overall, we identified 22 candidates for participation in the interviews, who were then contact by email. Of the 22 individuals contacted, 12 (54%) agreed to participate in the study. All of the individuals who were interviewed as part of this study are high-level technical professionals with great familiarity with recycled water issues in California, and work with recycled water issues on a daily basis for their profession.

Interviews and analysis.

We conducted 11 interviews by telephone during Winter and Spring 2016; 10 of the interviews were with individuals and one interview included two respondents. All interviews were audio-recorded with the permission of the respondents; interviews were recorded with the iPhone application TapeACall. The interviews were conducted using an open-ended interview format, which included three main themes with open-ended questions regarding barriers to expansion of recycled water use, future potential for expansion of recycled water use, potential for expansion of DPR, health impacts related to recycled water uses, and public perception of recycled water over time. (See **Table 4-1**.) Interviews averaged 30 minutes. Respondents were not offered monetary compensation for study participation. Identifying (i.e., name and workplace) information was removed during transcription, though metadata remained (e.g., area of expertise). Interview transcripts were transcribed manually in Scrivener, a word processing and project management program (Scrivener can be found at https://www.literatureandlatte.com/scrivener.php).

Analysis.

Our analysis began with a bottom-up coding approach using a grounded theory model, wherein the codes to tag the data were generated by themes within the data collected.[30] The grounded theory method uses a hypothesis-generating process, not a hypothesis testing process, which allows the data, codes, and themes generated to drive the development of the hypothesis.[30] Transcripts were tagged with the following codes, which were identified initially through themes in our literature review, and refined during our interviews: "barriers to expansion," "regulatory," "technology," "public perception," "funding," "infrastructure," "health," and "future projections." Each code was grouped by stakeholder sector (wastewater supplier, government regulator, public health professional, water policy professional, and engineers and consultants). Through our bottom-up coding process, we identified patterns, inconsistences, omissions, and additions across codes and groupings to help guide our analysis.

RESULTS

Our initial goal was to systematically identify barriers to the expansion of recycled water use in California. Three categories of barriers were identified through the literature review: barriers related to regulations, barriers related to technology, and barriers related to public perception. Three additional barriers were identified through the interviews with key stakeholders: barriers related to funding, barriers related to infrastructure, and barriers related to health. Respondents discussed encountering these barriers to expanding recycled water in their daily work, how they anticipate overcoming these barriers, and what outcomes we can expect for recycled water in the future. Although we initially intended to focus on barriers to expansion of recycled water treated for potable reuse, respondents described barriers for recycled water treated for both potable and

non-potable reuse. Subsequently, we discuss barriers identified for each of the six categories (regulatory barriers, technological barriers, barriers related to public perception, funding barriers, infrastructure barriers, and barriers related to health). In each case, the barriers are discussed according to whether they were identified as barriers to expanded use of recycled water for potable or non-potable reuse.

Regulatory barriers.

All respondents spoke at length about regulations as barriers to recycled water use. The examples of regulatory barriers they identified ranged from changes needed in building codes to a lack of regulations for DPR.

Regulatory barriers related to non-potable reuse. Several respondents (including one or more engineers, consultants, and public health professionals) identified specific components of building codes that, if amended, they believed would lead to more expedient expansion of recycled water for non-potable use in California. Several respondents noted that the current plumbing code allows residences to use gray water systems in-home for spray irrigation, though current code is not written to allow use of recycled water in homes for flushing toilets. Respondents noted that amending the plumbing code to allow recycled water use in toilet flushing could be an additional way to help homeowners conserve freshwater. Respondents felt this amendment to the plumbing code is worth considering, especially when installing plumbing systems for new housing developments.

Several respondents also mentioned that regulatory changes are necessary to allow use of recycled water for toilet and urinal flushing in high-rise buildings, which would also provide fresh water savings. One respondent clarified:

> To introduce recycled water into high rises, a dual-plumbed system is necessary to prevent cross contamination between the potable and recycled waters. In the case of any complications, a piece of hardware known as a "swivel ell" allows the user to switch between potable or recycled water distribution systems [which maintains an air gap between the water sources]. Switching systems allows potable water to flow in place of recycled in case something goes wrong. Right now, regulators aren't allowing these tools to be used on dual plumbed sites, and there is no mention [of] swivel ells within building code regulations, which slows down the potential to convert existing high rise buildings for use of recycled water.

Regulatory barriers related to potable reuse. One or more respondents from each of the stakeholder groups (wastewater supplier, government regulator, public health professional, water policy professional, and engineers and consultants) reported that a critical first step to expanding potable reuse in California would be the creation and adoption of regulations to support DPR. All respondents from wastewater suppliers and government regulatory agencies indicated that they felt the lack of regulations supporting DPR is the greatest barrier to expansion of recycled water use in California. One respondent from a government regulatory agency explained:

> To date, adoption of regulations for indirect potable reuse (IPR) in 2014 inspired development for 17 proposed IPR projects across the state. It is assumed that the same level of interest will result for DPR projects once regulations are put in place.

Respondents from wastewater suppliers, engineers, and consultants offered suggestions for how future regulations for DPR could be framed to ensure the best possible water quality. One respondent offered two options for dealing with potential lapses in treatment, which were echoed by others:

> *(1) Real-time monitoring for water quality concerns (pathogens, chemicals of emerging concern, nitrogen) could be implemented into the DPR system as an alert for any problems. To supplement the real-time monitoring, a method for immediate action to prevent contaminated water from entering the potable water supply should be included in the event the water does not meet all quality requirements or, (2) Storing and testing the treated water before allowing its entry into the potable water system. This would allow a greater time buffer to act if any problems arise.*

In addition to pointing out the need for setting regulations for DPR, two respondents from regulatory and wastewater supply sectors mentioned the significance of regulatory standards for hiring and training operators to manage DPR facilities. For instance, one stated:

> Once DPR facilities are ready for use, hiring and training operators to manage the facilities effectively will be an important step. To ensure operators are fully trained to fix any problems, and educated to monitor and prevent any potential water quality issues, a certification program and test should be developed now so it's ready to go.

Overall, the belief that the lack of regulations for DPR is the greatest barrier to expanded recycled water use was consistent among all respondents. Regulators, engineers, consultants,

wastewater suppliers, and public health officials that we interviewed prioritized regulations to assure water quality, while wastewater suppliers and regulators that we interviewed called attention to the need for regulations monitoring operations at the treatment facilities.

Technological barriers.

Technological barriers related to non-potable reuse. Overall, the experts we interviewed agreed that technology is available and effective for treating wastewater for non-potable uses.

Technological barriers related to potable reuse. By contrast, there was no clear consensus among the respondents we interviewed regarding whether technological barriers are a concern for expansion of DPR, particularly whether current technologies are adequate to treat water for potable reuse. One wastewater supply professional we interviewed stated, "The technology for direct potable reuse is there. We can treat water to such a high level, that by the time it leaves the plant, there's nothing in it."

Several of the engineers, consultants, and public health professionals expressed concern that the water treatment technology is not adequate to remove pathogens and chemicals of emerging concern. Despite this trepidation regarding technological advances, respondents from all of the stakeholder groups expressed confidence that the technological barriers will be addressed and DPR will be integrated into California's water supply within the near future, with estimates for achieving this ranging between 5-20 years.

Infrastructure barriers.

Infrastructure barriers to recycled water use were identified by wastewater suppliers, engineers and consultants, and public health professionals. As the situation currently stands, the infrastructure in place at most wastewater treatment facilities does not support the need for DPR. Wastewater suppliers we interviewed identified concerns about building out their facilities for new uses, and for rerouting existing water through their plants; engineers and consultants we interviewed mentioned concerns about building out infrastructure for new technology; and public health professionals identified infrastructural needs related to inspecting and approving plans for new buildings sites.

Infrastructure barriers to non-potable reuse. Two respondents mentioned an unintended consequence of increasing water conservation could be reduced flows at wastewater treatment plants. One respondent pointed out that they are already experiencing challenges:

> Originally treatment plants were located to best access more residential flows and avoid industrial discharges to get the highest quality recycled water. Currently, the service area is limited and now there aren't as many places to get recycled water.

Another respondent pointed out:

> Not all wastewater treatment facilities are set up to distribute recycled water back into the community they came from; some are set up to route all treated water directly to the ocean. Infrastructure updates to piping would help reroute flows to maximize uses at facilities with decreasing flows, and also to reduce waste.

Infrastructure barriers to potable reuse. Respondents we interviewed from wastewater suppliers indicated that investments in infrastructure for DPR would minimize the need for pipeline updates to transport recycled water to environmental buffer locations (which are necessary for IPR), or for piping for non-potable reuse (also known as "purple pipe"). One respondent mentioned that DPR may be more readily adopted in locations where suitable surface or groundwater storage buffers are not possible due to soil type or groundwater basin contamination.

Funding barriers.

Funding was identified as a major barrier to expanding recycled water for both non-potable and potable uses, as lack of sufficient funding impedes the implementation of necessary infrastructure and technology updates for expanding reuse. Funding barriers to expanded recycled water use were identified by government regulators, water policy professionals, wastewater suppliers, and consultants and engineers that we interviewed.

Funding barriers to non-potable reuse. One example of a successful approach to provide funding for water recycling projects that was cited by several respondents from a variety of stakeholder groups was California's SWRCB program, which offers loan money for recycled water projects. Since the SWRCB program was implemented in 2015, so many agencies have taken advantage of these resources that the initial allocation of $800 million for the program had to be supplemented with an additional $100 million in discretionary funds. Several stakeholders also mentioned funding from California's 2014 Proposition 1 water bonds, which provided $725 million in funding for recycled water; one respondent noted that funds from the Proposition 1

water bond are running out quickly.[31] Water policy professionals and wastewater suppliers that we interviewed noted an alternative to accepting funding or loans from the state would be for individual water suppliers to increase rates to support infrastructure costs. However, these respondents also noted that rate increases are not a preferred solution in most areas, especially if water suppliers wish to maintain a positive association with increased use of recycled water.

Several respondents pointed out that obtaining funding for end-users (e.g., schools) to implement recycled water systems for non-potable reuse on their properties can be challenging. Government regulators and engineers and consultants that we interviewed mentioned barriers related to funding for end-users to implement recycled water systems for non-potable reuse on their properties. Currently, funding regulations only allow water suppliers to apply for funding for recycled water projects. This stipulation fails to recognize that designing, planning, and creating infrastructure to receive recycled water is costly. One respondent noted that programs can be implemented to help overcome this barrier:

> Currently, if a school is interested in using recycled water to irrigate its sports fields, the school is responsible for the cost of retrofits and connections once the recycled water reaches their property. To amend this, Southern California's Metropolitan Water District previously sponsored a program to support funding required by the end-users, though this is not the norm… Metropolitan Water District allocated $7.2 million towards end-user support for expansion of recycled water infrastructure.

Several respondents suggested that funding opportunities for end-users should be included within future calls for funding by the state and other relevant funding entities.

Funding barriers to potable reuse. Funding barriers to implementing potable reuse of recycled water are even greater than those for non-potable reuse because of the additional infrastructure that would need to be put into place. Recognition of this barrier by California's SWRCB has allocated funding towards recycled water projects, which will allow local water districts to begin construction for potable reuse plants through SWRCB's subsidies.

In addition to securing appropriate funding, respondents stressed that water districts want to make sure it is economically viable to transition away from imported water and increase use of recycled water. They pointed out that the costs of implementing potable water reuse are too high, which could trigger backlash from their customers. Additionally, some respondents mentioned that a lack of funding could cause some areas to decide against implementing potable reuse, which could compromise the sustainability of their water supply and increase costs as imported water costs increase. Three respondents mentioned that funding is a particular concern for smaller or lower income communities who may not have the capital to implement recycled water systems.

In many instances, infrastructure and funding challenges are not mutually exclusive. One respondent mentioned that one way to minimize both infrastructure and funding challenges is through greater regionalization of water systems:

> We would hope there would be more regionalization of recycled water systems, but this hasn't been the case until recently when Southern California's Metropolitan Water District voted to do a pilot study on recycled water for indirect potable reuse in

collaboration with Los Angeles County Sanitation. If this turns out well, they'll expand to treat Los Angeles County effluent and distribute to all their member agencies.

Several respondents noted that cooperation between districts is becoming more common, and that it should be an important next step in ensuring successful expansion of potable reuse.

Public perception.

All stakeholders we interviewed mentioned that public perception and acceptance of recycled water has changed immensely over the past 20 years, especially in response to California's current drought.

Public perception barriers to non-potable reuse. Respondents noted that whereas barriers related to public perception were once an intractable issue for expanding recycled water, perception has evolved over the last twenty years, thanks in large part to public education campaigns. Some essential factors that respondents highlighted as being important for maintaining a positive public association with recycled water are:

- Keeping the public informed early on regarding when wastewater will be integrated into their water sources, the treatment type, and how treatment occurs;
- Promoting education programs at wastewater treatment plants; and
- Maintaining consistent terminology.

Several respondents cited public tours of wastewater treatment plants as one of the best methods for gaining public trust, as well as word of mouth. In one respondent's experience:

> Public perception has evolved a lot because of the drought. Now people are asking to learn about recycled water, not shying away from it. Everyone has been extremely careful to make sure we're not moving too quickly and moving ahead of the science and experts, and keeping the public on board.

Public perception barriers to potable reuse. Another respondent mentioned that the public isn't knowledgeable of different treatment types for recycled water; thus, labeling recycled water treated for non-potable reuse as "do not drink" could send a negative message for public perception of recycled water treated for potable reuse once its available in more communities:

> *As people began to learn how water can be recycled and that it's put into purple pipes, there's been a lot of approval. But at the same time, two opposing things were happening:*
>
> *1. More information was getting out about the potential for pharmaceuticals passing through treatment systems and making the water dangerous, and*
>
> *2. There has been very confusing language on signage all over the place.*
>
> *On one hand, the signs will report "we use recycled water for irrigating," but in others, it will say "do not drink," which sends very conflicting messages.*
>
> *This has definitely led to more awareness, and more acceptance, but the confusion and inconsistencies can also create fear.*

This respondent advocated for consistent messaging and terminology for all types of recycled water, which would help to lessen public fears and increase public acceptance of recycled water.

Health risks.

Potential health risks associated with recycled water use are at the root of most public perception fears[17] and were also cited by some of our respondents as a potential barrier to application of recycled water for potable use.

Health risk barriers to non-potable reuse. Although most respondents did not express concerns about human health risks related to non-potable reuse of recycled water, some wastewater suppliers had concerns regarding the salinity of water sources and its impact on the local environment, which can in turn impact human health. One explained:

> For irrigation use, the barrier we need to address to be more expansive about use is salinity. Conservation has driven natural salinity levels up and there are certain plant types that don't do well and die with higher salinity if there isn't sufficient flushing of the soil with lesser salty water. We've seen this increase over time principally because of conservation and it depends on which source quality is available to the jurisdiction.

Health risk barriers to potable reuse. By contrast, several respondents (including consultants and engineers, and public health professionals) mentioned potential human health risks as a barrier to DPR in the future. Respondents were adamant about ensuring that treatment technology keeps up with emerging challenges if use of recycled water for potable applications is to be implemented in California. Some respondents mentioned discussions within the water community about concerns regarding handling effluent from industrial sources and storm water, which could alter water quality and introduce new chemicals into the water supply unpredictably. Other respondents mentioned nitrification of the water caused by decreased water flow, and some

raised concerns raised by constituents about whether emerging concern and pathogens would pose a risk if recycled water is included in the water supply for potable use. For instance, one respondent suggested:

> It will be necessary to determine levels for acceptable risk for drinking water [for chemicals of emerging concern and pathogens]. It is essential that sensor technology for direct potable reuse is proven effective before it is implemented for drinking water, otherwise public trust will be lost. Consistency of treatment and its ability to be 100% reliable over time is an issue, and the next few years will be important for improving health-related sensor technology for use in direct potable reuse buffering systems.

Another respondent clarified why wastewater suppliers are most concerned about pathogens, and methods for determining the treated water was safe and pathogen-free:

> The pathogens are very important to control because they represent acute risks. It's not like the chemicals of emerging concern, where some involve long-term risks so presence the of some chemical above its MCL [maximum contaminant level] for a very short time period and it wouldn't be very meaningful because it could be taken care of with proper treatment….While both pathogens and chemicals of emerging concern are important from a regulatory standpoint through on-line monitoring and surveillance, pathogens are what we're most concerned about controlling from a health standpoint.

For how to best control for pathogens as many pathogens as possible to protect health, the same respondent suggested:

> You don't need to monitor for all pathogens — in fact, you can't because it's too expensive. Not only can you not monitor for all pathogens, but you can't do it in a fast enough time period because as soon as you get the [water quality] results, the water is long-gone. Existing pathogen knowledge is based on existing research where we've looked at the most resistant pathogens, for example viruses that are likely to be present in the water and monitor for those…Given current treatment technology using reverse osmosis and AOP [advanced oxidation processes], we are relatively confident that the water is clear, though, there's more to be done and more studies should be conducted to determine of what's present in raw, untreated wastewater in the future.

DISCUSSION

Out of the six categories of barriers to expanded use of recycled water in California identified by respondents (regulatory barriers, technological barriers, barriers related to public perception, funding barriers, infrastructure barriers, and barriers related to health), the barrier category that was identified consistently as the most pressing were those associated with regulations. Although some barriers, such as public perception, were mentioned by all groups of respondents, other barriers emphasized by some types of professionals were not mentioned by other respondents. (See **Table 4-2**.) Many of these were not surprising; government regulatory employees identified regulatory barriers, public health professionals discussed health barriers, and engineers and consultants brought up technological barriers. Interestingly, respondents who mentioned health concerns also tended to be the same ones who emphasized technical barriers. Regulatory barriers, such as the need for regulations for DPR, were mentioned by most respondents. Among

the different barriers discussed by respondents, regulatory barriers seem most amenable to change.

As has been reported previously in other studies and settings,[1,2,23,28,32,33] we found that the stakeholders in the recycled water and public health communities in California that we interviewed consistently recognized and valued the potential benefits of expanding recycled water use. While all stakeholders that we interviewed indicated that they supported expansion of recycled water for DPR, most spoke about DPR in hypothetical terms because DPR is not used currently in California.

Lessons learned: Importance of public perception barriers to recycled water.

Our interviews highlighted the importance of improving public perceptions of recycled water, especially at a project's beginning stages, and provided insights into how this can be achieved effectively. Respondents noted that public perception of recycled water typically improves with greater education, particularly about the benefits of recycled water. Our respondents suggested that adopting consistent language for recycled water can aid educational efforts. Among professionals, recycled water is also known as *reclaimed*, *reused*, or *purified* water, but the general public is typically unaware that these terms all refer to the same treated wastewater. Using consistent terminology in public health education materials could help inspire greater acceptance. Plain language should be used in all educational materials to ensure best absorption of the information by general population, and avoid using terms with negative connotations such as "toilet to tap.[21]" To create more consistent terminology, one of our respondents suggested recycled water treated for potable reuse could be plainly known as "drinking water" and recycled

water treated for non-potable uses could be known as “irrigation water,” which could help present the idea to the public in a non-intimidating format.

Lessons learned: Ways that public health professionals can contribute to lowering barriers to recycled water use.

The interviews that we conducted also suggested that public health professionals could play an important role in lowering barriers to recycled water use, even in cases where public health departments have no direct control over the issues at stake. When pointing to the factors that contributed to successful recycled water projects, several of our respondents emphasized the importance of inter-agency cooperation. In the examples the respondents cited, this typically involved a partnership between a local water district and its neighboring sanitation district, or between a local water district and its water wholesaler. Our respondents did not, however, identify partnerships between local water districts and public health departments. Ideally, these types of partnerships and collaborations will occur more frequently as public health departments, especially in drought-stricken California, expand their focus from safety of urban water supplies to system resiliency. Partnerships between water districts and public health departments could be advanced for soliciting funding as a joint unit, or creating a joint education and outreach campaign to promote the safety and health benefits of recycled water use. The importance of public health professionals engaging in these issues was highlighted by the results of a recent poll conducted by California’s SWRCB, “Public Attitudes Toward Potable Reuse of Recycled Water.” According to the poll, 77% of survey respondents rated the department of public health as the top organization to trust for information regarding safety of recycled water. This poll demonstrates that public health departments could play an important role in education of public

health practitioners, medical professionals, and local community groups about recycled water and its benefits. We noted that none of our respondents mentioned the potential health-related benefits of expanded recycled water beyond water quality issues. We believe that educating public health practitioners and medical professionals about the greater health-related benefits of expanded recycled water use would help them to provide the public with a more positive perception of recycled water.

LIMITATIONS

We employed a nonrandom, targeted convenience sampling strategy for our participant population. The findings of this study are limited by the sample size and nonrandom selection of respondents that emphasized representation of professional groups. Missing from this study is representation from local potable water suppliers, local governments, community leaders, medical professionals, public health practitioners outside the water community, environmental non-governmental organizations (NGOs), and academicians. Additional research to assess concerns of other stakeholders not included in this study—such as local government officials, community groups, medical professionals, potable water suppliers, academics, school groups, and environmental NGOs—would likely be informative. Local government officials and community groups may have provided insight into local infrastructure and funding needs, as well as a community perspective on integrating and expanding recycled water. Community groups, school groups, and environmental NGOs may have offered perspectives regarding building support of recycled water, or how to introduce the topic into the community because they understand the community's specific needs. Medical professionals may have provided perspectives on the idea of integrating knowledge about water source safety into the clinical

setting, or on writing educational materials for the public. Academics may have provided perspectives on developing technology and policy positions, what to expect in the future, and ways to communicate public health messages to the public effectively. We recognize that these stakeholder groups are valuable to the continuing conversation over the expansion of recycled water and hope future research involves these groups to better understand the breadth of the issue across all stakeholders.

In addition, although the individuals interviewed represented a wide range of views and expertise, the findings may still have been limited in breadth. The views, attitudes, and policies described in this study apply primarily to California. Despite limited direct applicability to other areas, these findings can guide further inquiry into perspectives in other areas. Future studies surveying randomized samples may provide more generalizable opinions from the water community, and from outside California.

We found that respondents' perspectives on recycled water focused on non-potable reuse and tended to omit consideration of potable reuse. This makes sense given the rarity of potable reuse. IPR is present at seven locations,[12] and DPR does not exist in California at all. Perhaps this bias gave a more generous perspective when asked about public perceptions related to DPR, but that remains to be seen in the future as DPR becomes a part of California's water supply.

CONCLUSIONS

The results from the interviews reported herein provide a nuanced understanding of the wide range of barriers that still exist to expansion of recycled water, particularly recycled water for

potable applications in California. These insights in turn provide specific, tractable recommendations for what steps must be taken if recycled water is to play a more important role in the future of California's water systems. One key insight gained from these interviews is that expanded use of recycled water in California will not occur without the creation and adoption of regulations to support DPR. In addition, once these regulations are in place, additional funding must be made available for implementation of the required systems.

The interviews also revealed that, although public perception of recycled water has improved, much work remains to be done if recycled water for potable applications is to become widespread in California. Water districts should focus on public outreach and education campaigns to inform constituents regarding potable water reuse and its advantages over other water sources. Plain language should be used in all documentation to ensure best absorption of the information by general population. Generating support from the public health community could help overcome public perception barriers to expansion by garnering public approval and helping expedite water reuse projects. Additionally, funding for staff dedicated to both education and infrastructure and maintenance for potable water reuse would help expedite expansion because public perception and manpower limitations are a big barrier to expansion.

REFERENCES FOR CHAPTER 4

1. Raucher R, Tchobanoglous G. The opportunities and economics of direct potable reuse. WateReuse Foundation: https://www.watereuse.org/product/14-08-1. Published 2014.
2. Leverenz H, Tchobanoglous G, Asano T. Direct potable reuse: A future imperative. *J Water Reuse Desal.* 2011;1(1):2-10.
3. Tchobanoglous G, Leverenz H, Nellor M, Crook J. *Direct Potable Reuse: A Path Forward.* WateReuse Research Foundation; 2011.
4. National Resources Council of the National Academies. *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater.* 2012.
5. United States Census Bureau. California quick facts. http://quickfacts.census.gov/qfd/states/06000.html. Published 2010.
6. MacDonald G. Water, climate change, and sustainability in the Southwest. *P Natl Acad Sci USA.* 2010;107(50).
7. Sutula MA, Lyons GS. Southern California Coastal Water Research Project. 2011 SCCWRP Annual Report: Effluent discharges to the Southern California Bight from large municipal wastewater treatment facilities from 2005 to 2009. http://ftp.sccwrp.org/pub/download/DOCUMENTS/AnnualReports/2011AnnualReport/ar11_223_236.pdf. Published 2011.
8. California State Water Resources Control Board. Water recycling funding program, municipal wastewater recycling survey. http://www.waterboards.ca.gov/water_issues/programs/grants_loans/water_recycling/munirec.shtml. Published 2011.

9. Newton D, Balgobin D, Badyal D, State Water Resources Control Board. Results, challenges, and future approaches to California's municipal wastewater recycling survey. http://www.waterboards.ca.gov/water_issues/programs/grants_loans/water_recycling/docs/article.pdf. Published 2010.

10. California Department of Water Resources. Managing an uncertain future: Climate change adaptation strategies for California's water. http://www.water.ca.gov/climatechange/docs/ClimateChangeWhitePaper.pdf. Published October 2008.

11. Tortajada C. Water management in Singapore. *Int J Water Resour D.* 2006;22(2):227-240.

12. WateReuse California. WRCA Potable Reuse Map. 2015.

13. Stoutenborough JW, Vedlitz A. public attitudes toward water management and drought in the United States. *J Water Res Man.* 2014;28(697).

14. Dolnicar S, Hurlimann A, Grun B. What affects public acceptance of recycled and desalinated water? *J Water Res.* 2011;45(2):933-943.

15. Ormerod KJ, Scott CA. Drinking wastewater: Public trust in potable water. *Sci Technol Hum Val.* 2013;38(3):351-373.

16. Fielding KS, Roiko AH. Providing information promotes greater public support for potable recycled water. *Water Res.* 2014;61:86-96.

17. Hartley TW. Public perception and participation in water reuse. *Desalination.* 2006;187(1–3):115-126.

18. Hurlimann A, Dolnicar S. Public acceptance and perceptions of alternative water sources: A comparative study in nine locations. *Int J Water Resour D.* 2016;32(4):650-673.

19. Garcia-Cuerva L, Berglund EZ, Binder AR. Public perceptions of water shortages, conservation behaviors and support for water reuse in the United States. *Resour Conserv Recy.* 2016;113:106-115.

20. Bridgeman J. Public perception towards water recycling in California. *Water Environ J.* 2004;18(3):150-154.

21. Water Education Foundation. *Layperson's Guide to Water Recycling.* 2013.

22. Jansen HP, Stenstrom MK, de Koning J. Development of indirect potable reuse in impacted areas of the United States. *Water Sci Tech.* 2007;55(1-2):357-366.

23. Toze S. Water reuse and health risks, real vs. perceived. *Desalination.* 2006;187(13):41-51.

24. Hartley T. Public perception and participation in water reuse. *Desalination.* 2005;187(1-3):115-126.

25. Tanaka H, Asano T, Schroeder ED, Tchobanoglous G. Estimating the safety of wastewater reclamation and reuse using enteric virus monitoring data. *Water Environ Res.* 1998;70(1):39-51.

26. Tchobanoglous G, Cotruvo J, Crook J, et al. *Framework for Direct Potable Reuse.* WateReuse Foundation, American Water Works Association, Water Environment Foundation, National Water Research Institute; 2015.

27. Cole BL, Sokolow S. *Pu*blic Health impacts of urban water conservation in California: opportunities to maximize co-benefits and minimize harm with case-study analysis of water conservation in the city of Burbank. Prepared by the UCLA Fielding School of Public Health's Health Impact Assessment Project in collaboration with The Los Angeles

County Department of Public Health http://www.ph.ucla.edu/hs/health-impact/reports.htm. Published 2014.

28. Sokolow S, Godwin H, Cole BL. Impacts of urban water conservation strategies on energy, greenhouse gas emissions, and health: Southern California as a case study. *Am J Public Health.* 2016;106(5).

29. Goodman L. Snowball sampling. *Ann Math Stat.* 1961;32(1):148-170.

30. Strauss A. *Qualitative Analysis for Social Scientists.* Cambridge University Press; 1987.

31. California State Assembly. *Assembly Bill 1471: The Water Quality, Supply and Infrastructure Improvement Act of 2014 that passed November 4, 2014 general election as Proposition 1.* 2014.

32. Anderson J. The Environmental Benefits of Water Recycling and Reuse. *Water Sci Tech-W Sup.* 2003;3(4):1-10.

33. Tanaka H, Asano, T, Schroeder, ED, Tchobanoglous, G. Estimating the safety of wastewater reclamation and reuse using enteric virus monitoring data. *Water Environ Res.* 1998;70(1):39-51.

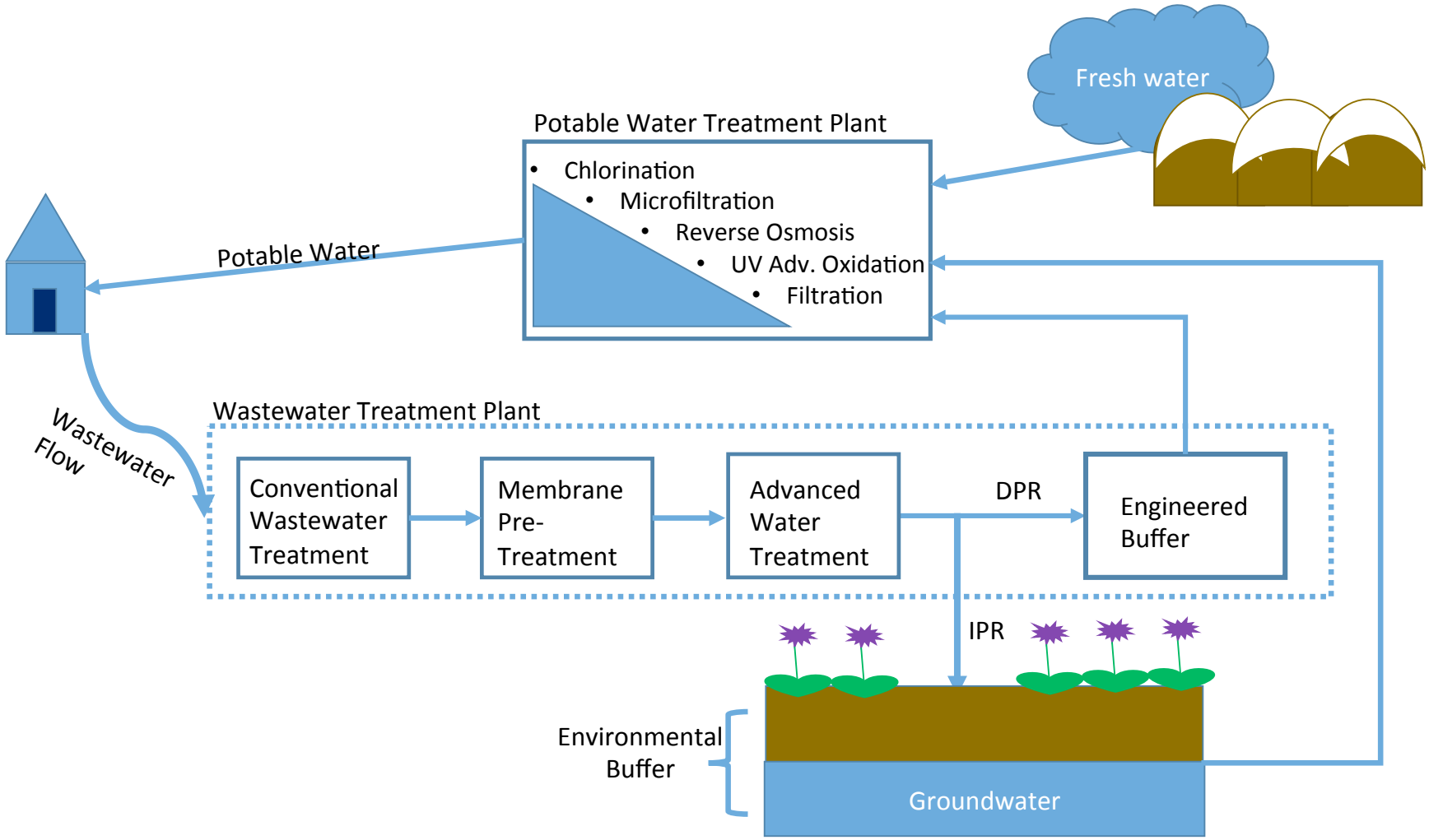

Figure 4-1: Comparison of treatment processes required for direct potable reuse (DPR) and indirect potable reuse (IPR) of recycled water. IPR utilizes an environmental buffer such as groundwater, or river, to provide final purification step, whereas DPR utilizes an engineered buffer within the wastewater treatment plant.

Table 4-1: Main interview questions

GENERAL QUESTIONS
1. What are the main issues that are important for your agency/organization to address around efforts to expand the use of recycled water? a. What are the greatest barriers you face in the expansion? b. How much influence does your organization have towards increasing the use of recycled water?
REGULATIONS & BARRIERS
1. Can you give any examples of urban recycled water uses your organization would like to pursue but are prevented from using due to current regulations? a. What should we anticipate in the next 10-20 years? 2. Describe urban recycled water uses that your agency/organization is currently developing but haven't implemented yet? 3. What happens in areas where the distance between recycled water sources and users is too far? 4. What do you think about smaller scale wastewater treatment options to increase use? Is this something your agency/organization is looking into? 5. What do you think needs to happen for direct potable reuse to be implemented? a. How far away from this are we? b. What barriers need to be removed? **c.** How is the division of drinking water involved?
HEALTH AND PUBLIC PERCEPTION
1. Have any health issues been raised re: your recycled water uses? If so, by whom, and what were the health concerns? 2. Do you think the public perception to potable reuse has evolved relative to 20 years ago, and where do you think it'll go in the future? 3. How do you feel about public perception in response to expanded potable reuse? 4. What efforts are being made to include public or improve public acceptance? What is your agency/organization doing?

Note. We conducted the interviews using an open-ended interview format. These interviews included three main themes with open-ended questions regarding barriers to expansion of recycled water use, future potential for expansion of recycled water use, potential for expansion of direct potable reuse, health-related impacts related to recycled water uses, and public perception of recycled water over time.

Table 4-2: Barriers identified by different types of stakeholders

Stakeholder Group	Barrier Areas					
	Regulatory	Technology	Public perception	Infrastructure	Health	Funding
Government Regulators*	●					●
Engineers & Consultants*		●	●	●	●	
Wastewater Suppliers*	●	●	●	●	●	●
Public Health Professionals*	●		●		●	●
Water Policy Professionals*	●		●			●
Potable Water Suppliers	●	●	●	●	●	
Local Government Officials	●		●	●		●
Community Groups			●			
Medical Professionals			●		●	
Environmental NGOs			●			
School Groups			●			
Academics		●	●		●	

Note. Respondents from five different stakeholder groups involved in recycled water implementation were interviewed for this study (denoted with *). The barriers to expansion of recycled water that they identified fell into six categories. Here, we show which categories of barriers were identified by each stakeholder group interviewed, and those barriers associated with groups outside this research.

CHAPTER 5

Overarching Conclusions and Recommendations for Future Studies

Southern California is just one of several highly populated regions of the world currently struggling with water scarcity or insecurity; these issues are projected to exacerbate further as a result of population growth and climate change.[1] Over the last century, Southern California has buffered itself from water insecurity by importing water from other parts of the American Southwest. However, greater demands on the region's water due to climate change and population growth across the entire American Southwest, coupled with increasing energy costs, challenge this strategy.[1-4] As a result, achieving more sustainable water management plans for Southern California is a high priority, and doing so could provide a model for other water-stressed regions.

One of several key strategies for improving sustainability of Southern California's water system is expanded use of recycled water.[5,6] However, despite recent legislation and initiatives aimed at increasing recycled water in California, the percentage of Southern California's water supply derived from recycled water—particularly for potable applications -- is quite low.[6,7] To affect an increase in recycled water used throughout California, a better understanding is needed of the benefits and barriers to expanding recycled water use, and how these barriers can be overcome. We evaluate this expansion through a lens for affecting change for the public's health. We recognize that the greatest changes to public health can be made outside the traditional purview of a doctor's office and that changes in arenas outside the medical profession can also improve

health. With the intention of recognizing that health exists in all policies, including water policies, we aimed to discover how the expansion of urban recycled water use can have impacts on public health, and to provide this information to decision makers. Specifically, we examined how water sources are both affected by and affect climate change, through a holistic examination of intermediate factors with downstream implications for health. While it is widely accepted that climate change will affect the quantity and frequency of droughts and floods across the world,[1,8,9] what is less recognized is how changes in water sources and water resources management will be affected by climate change, and how these decisions may impact health. Thus, by focusing our research on water sources, their sustainability, embedded energy and GHG emissions, water quality, costs, technical feasibility and public perception, we explored further how water sources are likely to impact public health in the future.

In this thesis, we have addressed these gaps through the following studies:

- **Chapter 2**: A systematic investigation of the health impacts (both positive and negative) of alternative water sources in Southern California compared to the health impacts of other effective water conservation strategies and status quo. We conducted this investigation by comparing energy demand and GHG emissions of these systems (published previously in the *American Journal of Public Health.*[10])
- **Chapter 3**: The development of a holistic framework to assess water source decisions at local water district and their potential to impact health. This holistic framework is operationalized using LBWD as a model, and includes a detailed qualitative analysis of sustainability considerations, water quality, technical feasibility, and public perception, as well as a quantitative analysis of the energy demand, GHG emissions, and costs of

different water source scenarios. Holistically assessing the potential health-related impacts of water source decisions can provide local water districts and decision makers with information to identify potential areas to minimize harm and maximize health-related benefits while choosing which water sources are best fit to their local circumstances.

- **Chapter 4**: An analysis of interviews with public health and water industry professionals to elucidate the barriers to expanding use of recycled water in California. This study sought to understand the barriers towards achieving the work evaluated in **Chapters 2** and **3**.

Subsequently, we summarize some of the overarching themes and insights that arose from this body of work, from the perspective of informing stakeholders wishing to advance the expanded use of recycled water. Although the work presented focuses on Southern California, the lessons learned herein should provide valuable information for other regions facing water insecurity, particularly those with similar climates and demographics.

THEMES AND INSIGHTS

Expanded Use of Recycled Water in Southern California Has the Potential to Result in Health Benefits, When Factors Related to the Water-Energy-GHG Nexus Are Considered

Whereas many prior studies on the health implications of expanded use of recycled water have focused on assessing the potential risks of recycled water stemming from water quality, we chose to focus on systematically assessing both the potential health risks and the potential health benefits of expanded use of recycled water when compared to other water source options.

In the study reported in **Chapter 2** (previously published in the *American Journal of Public Health*),[10,11] we used an HIA methodology[12,13] to compare the health impacts of alternative water sources (i.e., recycled water, desalination) to both bans on landscape irrigation (a widely touted water conservation approach, especially during the current drought) and the status quo (i.e., continuing to import the majority of Southern California's water over long distances). This study revealed that health impacts of water source choices in Southern California are tied to their respective energy demand, GHG emissions, and contribution to climate change. In addition, this study highlighted an important set of benefits associated with recycled water treated for non-potable reuse, namely the maintenance of green spaces that are conducive to health. Taken together, this analysis revealed that expanded use of recycled water for non-potable applications has the potential to improve health in Southern California when compared to either the status quo or other effective water conservation strategies. This result is noteworthy because it suggests that concerns about the health impacts of recycled water—particularly for non-potable applications—should not be cited as a barrier to expansion. Future studies could include collaboration between local health departments and water districts to develop evidence-based educational materials for the general public regarding health-related benefits associated with expanded use of recycled water.

In the study reported in **Chapter 3**, we sought to develop a framework for holistically evaluating the potential for health impacts when making water source decisions. Specifically, we sought to understand how expansion of recycled water for potable reuse could have downstream impacts on health compared to established water sources (imported water, groundwater, recycled water for non-potable reuse), recycled water for potable reuse, or seawater desalination. Within our

framework, we evaluated sustainability, water quality, costs, energy demand and GHG emissions, technical feasibility, and public perception of each source within a case study water district in Long Beach, California (LBWD). Understanding the impacts of incorporating recycled water for potable reuse within this holistic framework was important to explore for several reasons: (1) potable reuse is currently not a part of LBWD's water source portfolio, and this research helped determine its potential for health-related impacts in comparison to other source options; and (2) as climate change and water scarcity exacerbate, the need for recycled water treated for potable reuse will likely increase across drought-stricken regions.

To conduct this analysis, we qualitatively assessed sustainability, water quality, technical feasibility and public perception, and qualitatively analyzed energy, GHG emissions, and costs. Our qualitative analysis involved a literature review and discussions with key stakeholders, and our quantitative assessment used a modeling approach to compare the energy requirements for expanded use of recycled water (for potable and non-potable reuse) compared to other water source scenarios (imported water, groundwater, and seawater desalination) at LBWD over time. Development of this holistic framework allowed a greater understanding of all components of the water system and how changes may benefit or harm health. Our findings suggest that implementing recycled water for DPR could potentially result in an overall net-benefit to public health compared to imported water, groundwater, seawater desalination, or recycled water for non-potable reuse.

Public Health Professionals Can Play An Important Role in Promoting the Health-Related Benefits of Recycled Water by Working With Colleagues in Other Sectors to Advance the Safe and Appropriate Expansion of Recycled Water Use

The identification of health-related benefits associated with expanded use of recycled water in the studies presented in **Chapters 2** and **3** suggests that public health professionals could play valuable roles in promoting the safe and appropriate expansion of recycled water. Insights into the potential roles that public health professionals could play in the safe expansion of recycled water were gained from the stakeholder interviews we conducted, the results of which are reported in **Chapter 4**. An important theme that emerged through our interviews is that successful recycled water projects often involved a range of agencies working together, although public health departments were not part of these collaborations. This is a missed opportunity, both because public health professionals have expertise in developing educational programs and also because public health departments hold public trust. According to recent polling conducted for California's SWRCB focusing on "Public Attitudes Toward Potable Reuse of Recycled Water," 77% of participants rated the department of public health as the top organization they trust for information regarding safety of recycled water.[14] By collaborating with local water districts to develop public outreach and education campaigns about the benefits of recycled water, departments of public health could play an important role in promoting the resiliency of the water supply. Future studies in this area could include the development and assessment of training materials for public health professionals about the health-related benefits of expanded use of recycled water and the roles that they can play in the safe and appropriate expansion of this important water source.

Lessons Learned from this Work Regarding Recycled Water and its Barriers to Expansion in Southern California Have Broader Implications

Although the work presented herein focused on Southern California—and in the case of **Chapter 3**, a specific water district within Southern California—the insights we gained have broader implications. The observation that rising costs associated with importing water may render expanded use of recycled water more cost effective than the status quo has implications for water management across the region, and beyond. The observation that energy requirements and GHG emissions can dominate health impacts of water source decisions may be relevant to other regions with similar climates and socio-demographic factors, particularly urban areas in the Southwestern United States, and in high or middle-income countries within subtropical latitudes where precipitation is predicted to decrease, such as the Mediterranean, South Africa, parts of Mexico, and Australia. The methodologies for holistically and systematically assessing health-related benefits—sustainability, water quality, energy demand, GHG emissions, costs, technical feasibility and public perception—within different water source scenarios are broadly applicable and could be readily extended to provide evidence bases for decision making in other geographic regions of the world, including those with vastly different climates and socio-demographic factors. Likewise, the lessons learned through this work regarding how to improve communication strategies related to recycled water and the important role that public health professionals can play in developing and disseminating evidence-based educational materials are relevant worldwide. It is my sincere hope that this work will not only provide a sound evidence base for decision makers considering expansion of recycled water, but will also result in public health professionals playing a greater role in facilitating the safe and appropriate expansion of recycled water both locally and globally.

REFERENCES FOR CHAPTER 5

1. Intergovernmental Panel on Climate Change. *Climate change 2013: The physical science basis.* https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WGIAR5_SPM_brochure_en.pdf. Published 2013.
2. Cooley H, Christian-Smith J, Gleick P. *California's Next Million Acre-Feet: Saving Water, Energy and Money.* Oakland, CA: Pacific Institute; 2010.
3. Gleick P. *Waste Not, Want Not: The Potential for Urban Water Conservation in California.* Oakland: Pacific Institute; 2003.
4. Hanak E, Lund J. *Adapting California's Water Management to Climate Change.* San Francisco, CA: Public Policy Institute of California; 2008.
5. Water Education Foundation. *Layperson's Guide to Water Recycling;* 2013.
6. Raucher R, Tchobanoglous G. The opportunities and economics of direct potable reuse. WateReuse Foundation: https://www.watereuse.org/product/14-08-1. Published 2014.
7. California State Water Resources Control Board. *Water recycling funding program, municipal wastewater recycling survey.* http://www.waterboards.ca.gov/water_issues/programs/grants_loans/water_recycling/munirec.shtml. Published 2011.
8. Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. Impact of regional climate change on human health. *Nature.* 2005;438(7066):310-317.
9. California Department of Water Resources. *Managing an Uncertain Future: Climate Change Adaptation Strategies for California's Water.*

10. Sokolow S, Godwin H, Cole BL. Impacts of urban water conservation strategies on energy, greenhouse gas emissions, and health: Southern California as a case study. *Am J Public Health.* 2016;106(5).

11. Cole BL, Sokolow S. *Public health impacts of urban water conservation in California: Opportunities to maximize co-benefits and minimize harm with case-study analysis of water conservation in the city of Burbank.* Prepared by the UCLA Fielding School of Public Health's Health Impact Assessment Project in collaboration with The Los Angeles County Department of Public Health http://www.ph.ucla.edu/hs/health-impact/reports.htm. Published 2014.

12. Cole B, Shimkhada, R, Fielding JE, Kominski G, Morgenstern H. Methodologies for realizing the potential of health impact assessment. *Am J Prev Med.* 2005;28(4):382-389.

13. Cole B, Wilhelm M, Long P, Fielding J, Kominski G. Prospects for health impact assessment in the United States: New and improved environmental impact assessment or something different? *J Health Polit Polic.* 2004;29(6):1153-1186.

14. Data Instincts Public Outreach Consultants and Fairbank Maslin Maullin Metz & Associates. Public attitudes towards potable use of recycled water: Key findings from survey and focus group research. http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/recharge/agmtg9-item06-metz.pdf. Published 2016.

APPENDIX 1

Supporting Information for Chapter 3

SUPPLEMENTAL METHODS

Calculation of potential supply of wastewater available for reclamation and treatment for either DPR in LBWD.

To determine whether sufficient wastewater will be available in LBWD in 2025 and 2035 to be able to satisfy the demand for input water for treatment for DPR in the scenarios we explored, we created **Table 3-1** (Projected amount of water from each source assumed for each scenario in Long Beach Water District case study) to determine the water necessary to meet our needs.

In brief, our water demand scenarios were organized as follows:

Scenario 1 (S1) "Business as Usual" (BAU) reflects the current water source mix proposed for 2025 and 2035 in LBWD's 2010 urban water management plan.[1] This scenario assumes that LBWD will continue to rely on imported water, groundwater, and non-potable reuse, and will start to use a small amount of seawater desalination (5,000 AF in 2025 and 10,000 AF in 2035).

Scenario 2 (S2) "Mixed Reuse" (MIXED) was designed to explore the impacts of replacing both imported and desalinated water with recycled water treated for potable reuse.

Scenario 3 (S3) "Maximizing Potable Reuse" (POTABLE) was designed to explore the impacts of replacing imported, desalinated water, *and* recycled water treated for non-potable reuse with recycled water treated for potable reuse.

Scenario 4 (S4), "Maximizing Desalination" (DESAL) was designed to explore the impacts of replacing both imported and recycled water treated for non-potable reuse with desalinated water (and not treating any recycled water for potable reuse).

Water applications and system loss. To determine water applications and systems loss, we assumed that 59% of total water demand in LBWD is allocated towards outdoor uses and thus is unavailable for eventual reuse;[1] we also assumed that 5% of total water demand is lost to system leakage and thus is unavailable for eventual reuse.[1,2] The water remaining for indoor applications to be allocated as sewage, and thus available for wastewater treatment, is 36% of the total water demand.

Conventional wastewater treatment. To determine water demand for DPR in MIXED and POTABLE, we assumed that additional water could be made available from the LCWRP,[3,4] which is nearby to LBWD and, like LBWD's wastewater treatment facility, is also operated by the Los Angeles Sanitation District (LASD). This additional treated wastewater allows LBWD to meet the potable water needs of their population if DPR were to be implemented.

This calculation revealed additional water would be required from the LCWRP to supplement LBWD with enough water to supply their needs for water sources for NPR and DPR in 2025 and 2035. Our calculations assume that 11% of wastewater treated is "sludge" and thus unusable, and that the remaining 89% of wastewater influent can be treated and used within the service area.[1,3,4]

Detailed explanation of source of energy demand numbers provided in Table 3-1 and rationale for selection of these sources.

Imported water.

Conveyance of imported water. LBWD purchases its imported water from MWD and thus relies on MWD to convey water across California. MWD's conveyance energy is dependent on water traveling from the State Water Project through the California Aqueduct to MWD's East and West Branches. Conveyance energy demand to reach the East branch is 2,580 kWh/AF, and the energy to reach the West Branch is 3,236 kWh/AF, which results in an average energy demand of 2,908kWh/AF. MWD reported these numbers in a 2005 California Energy Commission Report,[5] which was confirmed by a senior engineer at MWD via public information request.[6]

This is the best available data for conveyance energy because MWD is the agency responsible for moving water between Northern and Southern California; limitation of this value is an estimate versus an exact value.

Treatment energy for potable water. Energy demand data were not available for treatment energy for potable water for LBWD. As a result, we forecasted LBWD's treatment energy demand based on relevant system parameters for LBWD and regression parameters estimated using data from a national survey of water utilities fielded by AwwaRF. A detailed explanation of the regression analyses is provided subsequently. The predictors for treatment energy include water source information (total annual water flow, purchased water flow, raw pumping horsepower) and treatment process information (oxidation, direct filtration, sand drying bed, ozone, and iron removal). These predictors explain 64% of variation in treatment energy among water utilities in

the national sample. The resulting estimate for energy demand to treat potable water at LBWD that was obtained from the regression-based forecast was 44 kWh/AF; the estimated uncertainty of this estimate was assumed to be ± 10 kWh/AF.

Distribution energy for potable water. The distribution energy represents pumping through the water distribution system (from the treatment facility) measured at pumping stations. Energy demand data were not available for distribution energy for potable water for LBWD. As a result, we estimated this energy demand using a similar regression-based forecast to that described above (further details presented subsequently). Eighty-one utilities in the AwwaRF survey reported distribution electricity in addition to distribution pump horsepower. The predictors of distribution energy include total annual water flow, distribution pumping horsepower, difference between highest and lowest points in system elevation, potential for lagoon dewatering, pressure filtration, and gravity thickening. These predictors explain 61% of variation in treatment energy among water utilities in the national sample. The estimated distribution energy demand for potable water sources for LBWD obtained from the regression-based forecast was 4.4 kWh/AF. Because the energy demand values for other components had an uncertainty of at least ± 10 kWh/AF, we listed this as < 10 kWh/AF in our table and used a range of 0-10 kWh/AF in our calculations.

Given the absence of distribution energy data directly from LBWD, this forecast is reasonable because it was calculated based on relevant LBWD system parameters and system, water use, and energy use data from a national sample of 81 water utilities. Although this value is the best

possible number given the lack of available data from LBWD, the limitation of this data is that it is a forecast and not an exact value from LBWD.

Groundwater.

Collection energy for groundwater (source pumping). Groundwater at LBWD is extracted from 800 feet below the surface at Southern California's WRD's Central Groundwater Basin. Energy demand for distribution of potable water was not available directly from LBWD. As a result, we estimated this energy demand using a regression-based forecast similar to that described previously (further details presented subsequently). Seventy-two utilities in the AwwaRF survey sample reported data for groundwater production electricity. The predictors in this model included source total water flow, water pumping horsepower, and average purchased water flow; the model explains 72% of variability in production energy. Forecast production energy demand given LBWD system parameters is 91 kWh/AF. This forecast is a reasonable value to use given the absence of exact data from LBWD; the limitation of using the forecast value is that it is an estimate and not an exact value from LBWD.

Treatment energy for potable water. Groundwater is treated to potable water standards, at the same facility, using the same technology and equipment in LBWD. Therefore the treatment energy demand for groundwater for LBWD was assumed to be the same as that estimate for imported freshwater (i.e., 44 kWh/AF ± 10 kWh/AF).

Energy demand data were not available for treatment energy for potable water for LBWD. As a result, we estimated this energy demand by performing a regression analysis using equations and

data obtained from AwwaRF. (A detailed explanation of how the regression analysis was performed is presented subsequently.) The predictors for treatment energy include water source information (purchased water flow, raw pumping horsepower) and treatment process information (oxidation, direct filtration, sand drying bed, ozone); they explain 66% of variation in treatment energy in the model. The resulting estimate for energy demand to treat potable water at LBWD that was obtained from the regression analysis was 44 kWh/AF; the estimated uncertainty of this estimate was assumed to be ± 10 kWh/AF.

Distribution and conveyance energy for potable water. The distribution energy represents water movement through the distribution system measured at pumping stations. Eighty-one utilities reported distribution electricity in addition to distribution pump horsepower. The predictors include distribution pumping horsepower, difference between highest and lowest points in system elevation, potential for lagoon dewatering, pressure filtration, and gravity thickening. Groundwater travels through the distribution system twice—initially after leaving the groundwater basin, and then after treatment—thus, this number is used twice. The estimated distribution energy demand for potable water sources for LBWD obtained from the regression analysis was 4.4 kWh/AF (multiplied by 2). Because the energy demand values for other components had an uncertainty of at least ± 10 kWh/AF, we listed this as < 10 kWh/AF in our table and used a range of 0-10 kWh/AF in our calculations.

Wastewater for non-potable reuse.

Collection energy for wastewater. LASD treats and provides recycled water for non-potable uses for LBWD. According to the LASD annual recycled water report[4], they estimate the energy

demand for wastewater treatment to be 30 kWh/AF with a range of **20-40**. This number was confirmed through personal communication with LASD staff.[7]

Treatment energy for non-potable reuse. LASD treats and provides recycled water for non-potable uses for LBWD. According to the LASD annual recycled water report[4], they estimate the energy demand for wastewater treatment to be 450 kWh/AF with a range of 400-500. This number was confirmed through personal communication with LASD staff.[7]

Discharge energy for non-potable reuse. LASD treats and provides recycled water for non-potable uses for LBWD. Unused wastewater from LBWD is discharged to Los Coyotes Creek, a nearby water body.[1] The energy demand for discharge estimated to be 2.6 kWh/AF, according to personal communication with LASD staff,[7] who provided information about energy demand for discharge and amount of water discharged per year for LBWD. Because the energy demand values for other components had an uncertainty of at least ± 10 kWh/AF, we listed this as < 10 kWh/AF in our table and used a range of 0-10 kWh/AF in our calculations.

Wastewater for DPR.

Collection energy for wastewater. LASD treats and provides recycled water for non-potable uses for LBWD. According to the LASD annual recycled water report[4], they estimate the energy demand for wastewater treatment to be 30 kWh/AF with a range of 20-40. This number was confirmed through personal communication with LASD staff.[7]

Treatment for DPR. Energy demand to treat wastewater via DPR is based on the energy demand for AWT at OCWD's Groundwater Replenishment District for its advanced treated water. The purpose of AWT is to produce water that meets all federal, state, and local potable water standards. This data is the best possible value to apply to LBWD because if LBWD were to implement DPR, it would most likely involve installation of an AWT system.[8,9] The energy demand for AWT reported by OCWD is between 1100-1500 kWh/AF (average = 1300 kWh/AF), per communication from staff at the OCWD in response to a public information request.[9,10]

Distribution energy for potable water. Because DPR is treated for potable purposes, its distribution energy demand will be the same as for other potable water sources. The estimated distribution energy demand for potable water sources for LBWD obtained from the regression analysis was 4.4 kWh/AF. Because the energy demand values for other components had an uncertainty of at least ± 10 kWh/AF, we listed this as < 10 kWh/AF in our table and used a range of 0-10 kWh/AF in our calculations.

Desalinated Seawater.

Treatment energy for desalinated seawater. The estimated energy demand values for treatment of desalinated water for LBWD are on energy demand values found within "A Perspectve on Reverse Osmosis Water Desalination: Quest for Sustainability."[18] Since LBWD does not have its own seawater desalination plant, we used data to represent the energy demand range for seawater reverse osmosis given existing facilities.[18] The range for seawater desalination via reverse osmosis is between 3700-9250 kWh/AF.[18]

Distribution energy for potable water. Because desalinated seawater is treated for potable purposes, its distribution energy demand will be the same as imported water or groundwater. The estimated distribution energy demand for potable water sources for LBWD obtained from the regression analysis was 4.4 kWh/AF (multiplied by 2). Because the energy demand values for other components had an uncertainty of at least ± 10 kWh/AF, we listed this as < 10 kWh/AF in our table and used a range of 0-10 kWh/AF in our calculations.

Detailed methods for regression analysis to estimate missing energy demand data.

Energy demand for phases (e.g., production, treatment, distribution) associated with water sources used by LBWD was not available directly from the utility. To estimate these energy demands, we conducted forecasts based on regression analyses using data from a national survey of water utilities conducted by AwwaRF. Of note, the survey included 125 water utilities and 266 wastewater treatment plants across the United States, including a total of 46 in California. Our approach to the regression analyses were informed by methodology and variable selection detailed in an AwwaRF report titled, "Energy Index Development for Benchmarking Water and Wastewater Utilities."[11] The authors of the AwwaRF report used a stepwise approach to identify system parameters significantly associated with energy use. First, they used bivariate models to identify total flow as the strongest predictor of total energy use and energy use for each phase (e.g., treatment). Next, they ran a series of two-predictor models to identify parameters associated with energy use after adjustment for total flow. They then selected variables with *t*-statistic values ≥ 2.0 (roughly equivalent to a p value with statistical significance < 0.05) in these two-predictor models for inclusion in more robust models. The authors identified an "ideal" model (i.e., best balance between parsimony and R^2) for predicting total energy use that included

parameters relating to distribution and pumping (total average water flow, average purchased water flow, length of water mains, source water pump horsepower, total system horsepower, and elevation range).

For the purposes of this thesis, we conducted additional regression analyses using a parallel approach to that described above and used in the AwwaRF report. Our intent in conducting these additional analyses (rather than using the regression parameters reported in the report for our forecasts) was twofold. First, we sought to confirm the findings in the report. Second, the outcome variable (e.g., treatment energy demand) in each of the phase-specific regression models included energy purchased from energy utilities specifically for that phase (e.g., purchased energy for water treatment), plus natural gas used by the utility as a whole. This approach worked for AwwaRF, because the survey measured natural gas use for each utility as a whole (in other words, there is no way to include phase-specific natural gas use because the data were not collected for each phase). However, this approach did not fit our intended purpose of separately forecasting LBWD's energy demand for production, treatment, and distribution and then summing these phase-specific demands as an estimator of total energy demand. Essentially, including each utility's total natural gas use in the outcome for each phase and then summing to predict total energy demand results in over-estimation of total energy on the order of magnitude of double the mean natural gas use of utilities in the sample (because total natural gas use would essentially be triple counted instead of being counted once).

We used three multiple linear regression models to predict energy demand for the following among the 125 water utilities in the AwwaRF sample: (1) production energy demand,

(2) treatment energy demand, and (3) distribution energy demand. Energy demand outcomes for each outcome was measured in kBTU and log transformed to produce a more normal distribution (because there were many very large and very small utilities in the sample). Our approach to variable selection was to use variables identified in the AwwaRF report (and described both subsequently and in Chapter 3) as being in the "best fit" model for each phase.

Regression equation for production energy demand. The equation used in the multiple linear regression model for production energy demand was:

$$\ln(prod_kBTU) = 9.03 + 0.59 * \ln(calc_flow) + .42 * \ln(raw_hp) - .086 * \ln(raw_p_aflow)$$

where $\ln(prod_kBTU)$ is the natural log of production energy demand, $\ln(calc_flow)$ is the natural log of total average flow, $\ln(raw_hp)$ is source water pumping horsepower, and $\ln(raw_p_aflow)$ is average purchased water flow.

Regression equation for treatment energy demand. The equation used in the multiple linear regression model for treatment energy demand was:

$$\ln(treat_kBTU) = 9.90 + .69 * \ln(calc_flow) - .11 * \ln(raw_p_aflow) + .13 * \ln(raw_hp) + .80 * treat_ox - .79 * filt_dir - .66 * res_sand - .90 * treat_iron + .57 * proc_OZ$$

where $\ln(treat_kBTU)$ is the natural log of treatment energy demand, $\ln(calc_flow)$ is the natural log of total average flow, $\ln(raw_p_aflow)$ is average purchased water flow, $\ln(raw_hp)$ is source water pumping horsepower, $treat_ox$ is oxidation treatment, $filt_dir$ is direct filtration, res_sand is sand drying bed, $treat_iron$ is iron removal treatment, and $proc_OZ$ is ozone treatment.

Regression equation for distribution energy demand. The equation used in the multiple linear regression model for distribution energy demand was:

$$\ln(dist_kBTU) = 6.63 + .24 * \ln(calc_flow) + .74 * \ln(dist_hp) + .42 * \ln(elev_ch) - .38 * res_lag - 1.57 * proc_filt_press + .74 * res_grav$$

where $\ln(dist_kBTU)$ is the natural log of distribution energy demand, $\ln(calc_flow)$ is the natural log of total average flow, $\ln(dist_hp)$ is distribution pumping horsepower, $\ln(elev_ch)$ is the natural log of elevation change, res_lag is lagoon dewatering thickening, $proc_filt_press$ is pressure filtration, and res_grav is gravity thickening.

Forecasts. We used the regression parameters from each of the phase-specific models with information regarding LBWD system parameters (**see Table A1-1**) to forecast phase-specific energy demand for LBWD, resulting in three energy demand values: (1) forecast production energy demand, (2) forecast treatment energy demand, and (3) forecast distribution energy demand. We obtained system parameters for LBWD by identifying LBWD in the AwwaRF data based on state (i.e., California), population size, area size, number of groundwater pumps, and

length of water mains reported in the data set; we confirmed each of these system parameters separately with staff at LBWD.

Detailed information about sources of estimate costs for LWBD water sources.

The estimated unit price (in dollars per AF) for current and potential water sources for the LBWD are provided in **Table 3-4.** More detailed explanations of the sources of these costs estimates and why those sources were selected as the best available estimate are provided for each water source for LBWD subsequently.

Imported water. A unit price of $850-1,300/AF with a projected 9% annual increase in cost from 2010-2035 was used for the LBWD case study. The 2010 cost represent the price for water sold to water districts by the MWD, which is the current supplier of imported water for LBWD.[1] The projected increase in cost of 9-10% annually was obtained from MWD meeting minutes and local newspaper reports and is based on projections for future drought conditions and infrastructure needs.[12-15] The cost range represents a tiered water rate depending on usage, maintenance of conveyance and distribution facilities, treatment costs, power costs, and surcharges to invest in future water needs.

Groundwater. A unit price of $257-426/AF was used for groundwater for the LBWD case study. This range was given as the amount that the LBWD has paid for their groundwater over the past 10 years, in response to a public information request.[16] The LBWD purchases their water from WRD's Central Basin, then treats and sells the water at their own facilities. The overall cost for groundwater can be broken down into two parts (each roughly 50% of the cost, depending on the

year): WRD groundwater basin replenishment fee, and an additional cost for treating the water the water.[16] Overall, costs are higher during drought years because the costs for replenishing the groundwater basin and the depth groundwater is pumped result in higher cost.

Non-potable reuse. A unit price of $585-805/AF was used for the cost of water treated for non-potable reuse the LBWD case study. LBWD's recycled water is generated and treated by a facility operated by LASD. The price range used herein was that reported by LASD for the years 2014-15.[4] The cost range is representative of peak and off-peak demand times, in addition to operations costs. LASD sells the recycled water to LBWD at a rate of $804.55/AF for peak demand (nighttime) usage or $574.56/AF for off-peak demand (daytime) usage; $391 of this cost can be attributed to operations and management costs.[4]

Seawater desalination. A unit price of $654-2122/AF was used for the cost of desalinated water treated for potable use in the LBWD case study. Currently, LBWD does not use desalinated water. Thus, the range used herein are the costs reported within "A Perspective on Reverse Osmosis Water Desalination: Quest for Sustainability."[17,18] This text represents the most up-to-date values for seawater desalination via reverse osmosis given available technology.

The composition of seawater desalination facilities vary from location to location, thus no single facility's energy or cost profile can represent the needs of other facilities.[17,18] Generally, the factors causing and contributing to the overall cost and energy needs of a seawater desalination facility are the same from location to location. However, the magnitude of these factors can vary significantly between projects resulting in differences. According to the WateReuse Association's Desalination committee, factors include: local permit and regulation costs, intake

and discharge costs, feed water quality costs, finished water quality costs, project delivery mechanism costs, and associated infrastructure and operations costs (power, proximity, labor, etc.).[17,18] Despite the variety of factors contributing to desalination facilities, future costs for desalination facilities are trending downward, whereas imported water supplies are becoming more expensive.[18] The downtrend in overall seawater desalination costs is generally associated with improved Seawater Reverse Osmosis (SWRO) membrane performance and advances in energy recovery from the desalination process.[17,18]

DPR. A unit price of $700-900/AF was used for the cost of reclaimed water treated for direct potable use in the LBWD case study. Currently, LBWD does not treat recycled water for potable use and DPR is not currently used in California. To estimate the range of costs for DPR for LBWD, we used estimates for the cost for AWT of recycled water from OCWD. OCWD currently treats reclaimed water using AWT for their Groundwater Replenishment System, which treats recycled water for potable reuse via IPR. This is the same process that would be likely be implemented for treating recycled water for DPR if implemented at a facility in the future.

The total cost of DPR, including AWT, conveyance, and brine management, may run between $700/AF ($700/AF for AWT plus $120/AF for conveyance) and $900/AF. The low-end cost is based on the assumption that brine would be discharged through an existing ocean outfall. It is important to note that the cost of drinking water treatment (i.e., the cost to re-treat the AWT-generated water at the drinking water system treatment plant) is not included because the same quantity of water is being treated; only the source of supply has changed. Although OCWD received a grant from Orange County Sanitation District to pay for half the capital costs of their

project, this cost is not factored into this range, thus rendering it more generalizable to costs outside OCWD. Additionally, OCWD receives ongoing operating subsidies for energy programs and local water development from Southern California's MWD, although these are also not reflected within this cost range.

Table A1-1: Water demand calculations for water source scenarios within Chapter 3

Scenario	Year	Population	Sources (Acre-feet/year)						Water Applications and System Loss (Acre-feet/year)			
			Imported Water from MWD	Groundwater	Desalinated Water	Non-Potable Recycled Water	Potable Recycled	Total Inputs	Outdoor (not available for recycling) (% of inputs)	Indoor Applications "sewerage" (% of inputs)	Total Used (% of inputs)	Leakage (% of inputs)
(1) Business As Usual	Baseline 2010	462,257	22,237	34,655	0	6,556	0	63,448	37,434	22,841	60,276	3,172
			35.0%	54.6%	0.0%	10.3%	0.0%	100.0%	59.0%	36.0%	95.0%	5.0%
	2025	489,686	18,551	34,000	5,000	13,400	0	70,951	41,861	25,542	67,403	3,548
			26.1%	47.9%	7.0%	18.9%	0.0%	100.0%	59.0%	36.0%	95.0%	5.0%
	2035	508,233	11,929	35,000	10,000	14,000	0	70,929	41,848	25,534	67,383	3,546
			16.8%	49.3%	14.1%	19.7%	0.0%	100.0%	59.0%	36.0%	95.0%	5.0%
(2) Increasing Reuse	2025	489,686	0	34,000	0	13,400	23,551	70,951	41,861	25,542	67,403	3,548
			0.0%	47.9%	0.0%	18.9%	33.2%	100.0%	59.0%	36.0%	95.0%	5.0%
	2035	508,233	0	35,000	0	14,000	21,929	70,929	41,848	25,534	67,383	3,546
			0.0%	49.3%	0.0%	19.7%	30.9%	100.0%	59.0%	36.0%	95.0%	5.0%
(3) Maximizing Potable Reuse	2025	489,686	0	34,000	0	0	36,951	70,951	41,861	25,542	67,403	3,548
			0.0%	47.9%	0.0%	0.0%	52.1%	100.0%	59.0%	36.0%	95.0%	5.0%
	2035	508,233	0	35,000	0	0	35,929	70,929	41,848	25,534	67,383	3,546
			0.0%	49.3%	0.0%	0.0%	50.7%	100.0%	59.0%	36.0%	95.0%	5.0%
(4) Maximizing Desalination	2025	489,686	0	34,000	23,551	13,400	0	70,951	41,861	25,542	67,403	3,548
			0.0%	47.9%	33.2%	18.9%	0.0%	100.0%	59.0%	36.0%	95.0%	5.0%
	2035	508,233	0	35,000	21,929	14,000	0	70,929	41,848	25,534	67,383	3,546
			0.0%	49.3%	30.9%	19.7%	0.0%	100.0%	59.0%	36.0%	95.0%	5.0%

Table A1-2: Water demand calculations for water source scenarios within Chapter 3

Scenario	Year	Population	Conventional Wastewater Treatment (Acre-feet/year)					Advanced Treatment and Re-Use (Acre-feet/year)	
			Locally Treated Wastewater						
			Wastewater available for adv. treatment or reuse (@ LBWD)	Non-reusable Effluent Disposed from Wastewater Treatment (@ LBDWD)	Title 22 treated water needed from Los Coyotes	Total available for adv. treatment or reuse	Total Water Avail for Reuse (LBWD + LC)	Treated for non-potable available for reuse (% reuse water)	Treated for potable reuse (% reuse water)
(1) Business As Usual	Baseline 2010	462,257	20,329	2,513	0	20,329	22,841	6,556	0
			89.0%	11.0%	---	---	---	28.7%	0.0%
	2025	489,686	22,733	2,810	0	22,733	25,542	13,400	0
			89.0%	11.0%	---	---	---	52.5%	0.0%
	2035	508,233	22,726	2,809	0	22,726	25,534	14,000	0
			89.0%	11.0%	---	---	---	54.8%	0.0%
(2) Increasing Reuse	2025	489,686	22,733	2,810	14,218	36,951	39,761	13,400	26,361
			89.0%	11.0%	---	---	---	33.7%	66.3%
	2035	508,233	22,726	2,809	13,203	35,929	38,738	14,000	24,738
			89.0%	11.0%	---	---	---	36.1%	63.9%
(3) Maximizing Potable Reuse	2025	489,686	22,733	2,810	14,218	36,951	39,761	0	39,761
			89.0%	11.0%	---	---	---	0.0%	100.0%
	2035	508,233	22,726	2,809	13,203	35,929	38,738	0	38,738
			89.0%	11.0%	---	---	---	0.0%	100.0%
(4) Maximizing Desalination	2025	489,686	22,733	2,810	0	22,733	25,542	13,400	0
			89.0%	11.0%	---	---	---	52.5%	0.0%
	2035	508,233	22,726	2,809	0	22,726	25,534	14,000	0
			89.0%	11.0%	---	---	---	54.8%	0.0%

Table A1-3: Table of LBWD system parameters used in forecasts

	Groundwater Production (Extraction	Potable Water Treatment	Potable Water Distribution
Total Average Flow ($calc_flow$)	63.1	63.1	63.1
Source Water Pumping Horsepower (raw_hp)	3090	3090	--
Average Purchased Water Flow (raw_p_aflow)	38.4	38.4	--
Oxidation Treatment ($treat_ox$)	--	1	--
Direct Filtration Treatment ($filt_dir$)	--	0	--
Sand Drying Bed (res_sand)	--	0	--
Iron Removal Treatment ($treat_iron$)	--	1	--
Ozone Treatment ($proc_OZ$)	--	1	--
Distribution Pumping Horsepower ($dist_hp$)	--	--	2467
Elevation Change (lev_ch)	--	--	0
Lagoon Dewatering Thickening (res_lag)	--	--	0
Pressure Filtration ($proc_filt_press$)	--	--	0
Gravity Thickening (res_grav)	--	--	0

Note. With the exception of elevation change (which is a true zero), values of '1' and '0' are dummy codes to indicate whether a process is ('1') or is not ('0') used by LBWD.

REFERENCES FOR APPENDIX 1

1. Long Beach Water District. Long Beach Water District urban water management plan. http://www.lbwater.org/2010-urban-water-management-plan. Published 2010.
2. California Department of Water Resources. Water audit and leak detection. http://www.water.ca.gov/wateruseefficiency/leak/. Published 2017.
3. Los Angeles County Sanitation District. Los Coyotes Water Reclamation Plant. http://www.lacsd.org/wastewater/wwfacilities/joint_outfall_system_wrp/los_coyotes.asp. Published 2016.
4. Sanitation Districts of Los Angeles County. Twenty-sixth annual status report on recycled water use: Fiscal year 2014-2015. http://www.lacsd.org/civicax/filebank/blobdload.aspx?blobid=12648. Published 2016.
5. California Energy Commission. California's Water -- Energy Relationship (Final Staff Report). *Prepared in Support of the 2005 Energy Policy Report Proceeding (04-IEPR-01E);* 2005.
6. Scott J. Metropolitan Water District Request for Information: Conveyance Energy to Southern California. 2016. Email.
7. Hartling E. Energy Demand of Wastewater Treatment Process at Los Angeles County Sanitation District. 2016. Email.
8. Tchobanoglous G, Cotruvo J, Crook J, et al. *Framework for Direct Potable Reuse.* WateReuse Foundation, American Water Works Association, Water Environment Foundation, National Water Research Institute; 2015.
9. Raucher R, Tchobanoglous G. The opportunities and economics of direct potable reuse. WateReuse Foundation: https://www.watereuse.org/product/14-08-1. Published 2014.

10. Leverenz H, Tchobanoglous G, Asano T. Direct potable reuse: A future imperative. *J Water Reuse Desal.* 2011;1(1):2-10.

11. AWWA Research Foundation (AwwaRF); California Energy Commission; New York State Energy Research and Development Authority. *Energy Index Development for Benchmarking Water and Wastewater Utilities.* Denver, CO2007.

12. Metropolitan Water District of Southern California 4/8/2014 Board Meeting. Finance and insurance committee http://www.mwdh2o.com/PDF_Who_We_Are_Proposed_Water_Rates_n_Charges/2014-04-08-FnI-Board-Letter-8-1.pdf. Published April 2014.

13. Santa Margarita Water District. Rising imported water costs result in rates increase. http://www.smwd.com/assets/downloads/on-tap/On-Tap_2012-12.pdf. Published 2012.

14. Sforza T. Imported water prices: Up 96 percent since 2006. *Orange County Register.* http://www.ocregister.com/taxdollars/strong-478683-water-mwd.html. Published 2012.

15. Sforza T. Water Rates Double in 8 Years: Are You Getting Soaked? *Orange County Register* 2012: http://www.ocregister.com/taxdollars/strong-478657-water-percent.html.

16. Weatherly K. Groundwater Costs at Long Beach Water District. 2016. Email.

17. Cohen Y, Semiat R, Rahardianto A. A Perspective on Reverse Osmosis Water Desalination: Quest for Sustainability. *AIChe J.* 2017;63(6):1771-1784.

18. WateReuse Association Desalination Committee. *Desalination Water Costs White Paper.* https://watereuse.org/wp-content/uploads/2015/10/WateReuse_Desal_Cost_White_Paper.pdf 2012.