A comparative analysis of the health-related consequences of drought in the Po and Colorado river basins

by

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Abstract

Global climate change will continue to expose more communities to drought, a prominent environmental health hazard. Droughts, directly and indirectly, affect the health of nearby communities through reduced air and water quality, increased incidence of infectious disease, malnutrition, and poor mental health. Two regions in Europe and the United States faced with drought, the Po River Basin and the Colorado River Basin, provide an opportunity to understand how geography and policy affect the prevalence of the health-related consequences of drought. This thesis quantifies the drought conditions and relevant health-related consequences of drought in both the Po and Colorado River Basins to argue for the most salient public health challenge in each region. In the Po River Basin, heavy industry and natural geography render poor air quality the most salient challenge, and in the Colorado River Basin, the emerging disease coccidioidomycosis poses the most salient risk. By identifying the most salient health-related consequence of drought, public health practitioners and policymakers may more effectively target public health interventions and policies to reduce the burden of drought on public health.

Table of Contents

List of Figures vi
List of Tables viii
List of Abbreviations ix
Acknowledgments xi
Dedication xii
Chapter 1 - Introduction 1
Climate Change 1
Droughts and Definitions 2
Study Areas 3
Research Question and Methods 8
Anticipated benefits of the thesis 10
Thesis Structure 11
Chapter 2 - Health-related Consequences of Drought 12
Air Quality 12
Coccidioidomycosis (Valley Fever) 14
Water Safety 15
Mosquito-borne Diseases 16
Malnutrition 21
Migration 21
Mental Health 23
Discussion 23
Chapter 3 - Drought in the Colorado and Po River Basins 26
Methods: Data sets and analysis 31
Results and Discussion 32
Chapter 4 - Salient Challenges of the Colorado and Po River Basins 38
Methods: Data and Analysis 39
Results and Discussion 42
Chapter 5 - Conclusion 64
The Most Salient Challenge in the PRB 64

The Most Salient Challenge in the CRB 67
Recommended Public Health Interventions 69
Recommended Policies for Drought Resiliency 72
Future Directions 76
References 77

List of Figures

Figure 1-1; The Po River Basin. 4
Figure 1-2; The Colorado River Basin..... 4
Figure 1-3; Water and wastewater systems of a Roman *domus*. 8
Figure 2-1; Health-related effects of drought. 24
Figure 3-1; The *Zibello*, an Italian WWII supply barge, (left) and an American WWII landing craft (right). 26
Figure 3-2; SPEI-3 from 2012 to 2022. 33
Figure 3-3; SPEI-18 from 2012 to 2022. 34
Figure 3-4; SPEI-36 from 2012 to 2022. 35
Figure 3-5; Average TWSA from January 2022 to September 2023. 36
Figure 4-1; Average PM_{10} (A) and $PM_{2.5}$ (B) concentrations in the PRB from 2013–2021. 42
Figure 4-2; Annual average $PM_{2.5}$ (A) and PM_{10} (B) concentrations in the PRB. 43
Figure 4-3; Correlations between annual average PM_{10} concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the PRB. 43
Figure 4-4; Correlations between annual average $PM_{2.5}$ concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the PRB. 43
Figure 4-5; Average PM_{10} (A) and $PM_{2.5}$ (B) concentrations in the CRB from 2013–2022..... 44
Figure 4-6; Annual average $PM_{2.5}$ (A) and PM_{10} (B) concentrations in the CRB. 45
Figure 4-7; Correlations between annual average PM_{10} concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the CRB..... 45
Figure 4-8; Correlations between annual average $PM_{2.5}$ concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the CRB..... 45
Figure 4-9; Average Valley Fever incidence per 100,000 residents in the CRB from 2013-2022. 46
Figure 4-10; Annual Valley Fever cases and median incidence in the CRB. 47
Figure 4-11; Correlation between median Valley Fever incidence and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C). 47
Figure 4-12; Annual average nitrate (A) and phosphorus (B) concentrations in the PRB. 48

Figure 4-13; Correlations between average annual nitrate concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the PRB. 48
Figure 4-14; Correlations between average annual phosphorus concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the PRB. 49
Figure 4-15; Annual average nitrate (A) and phosphorus (B) concentrations in the CRB. 50
Figure 4-16; Correlations between average annual phosphorus concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the CRB. 50
Figure 4-17; Correlations between average annual nitrate concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the CRB. 50
Figure 4-18; Average annual WNV incidence in the PRB. 51
Figure 4-19; Annual average WNV cases (A) and number of provinces reporting (B) in the PRB. 52
Figure 4-20; Correlations between average annual WNV cases and number of provinces reporting and SPEI. 52
Figure 4-21; Annual WNV cases in the Lower (A) and the Upper CRB (C) and number of counties reporting in the Lower (B) and Upper (D) CRB. 54
Figure 4-22; Average annual WNV incidence in the CRB. 54
Figure 4-23; Correlations between total WNV cases and number of counties reporting and SPEI in the Lower CRB. 55
Figure 4-24; Correlations between total WNV cases and number of counties reporting and SPEI in the Lower CRB. 55
Figure 4-25; Average annual poverty incidence in the PRB. 56
Figure 4-26; Correlations between average annual poverty incidence and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the PRB. 57
Figure 4-27; Annual average poverty incidence in the PRB. 57
Figure 4-28; Average annual poverty rates in the CRB. 58
Figure 4-29; Annual average poverty rate in the CRB. 59
Figure 4-30; Correlations between average annual poverty rates and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the CRB. 59

List of Tables

Table 1-1; Colorado River allocations by state. 6
Table 1-2; Characteristics of the Colorado River Basin and the Po River Basin. 7
Table 3-1; SPEI values and their classifications. 31
Table 3-2; TWS values and their classifications. 31
Table 4-1; Air quality by pollutant. 38
Table 5-1; Summary of the health-related consequences of drought in the PRB. 66
Table 5-2; Summary of the health-related consequences of drought in the CRB. 69

List of Abbreviations

AIDS	Acquired Immune Deficiency Syndrome
AQI	Air Quality Index
CAP	Central Arizona Project
CDC	U.S. Centers for Disease Control and Prevention
CRB	Colorado River Basin
DFAA	Drought-Flood Abrupt Alternations
DNA	deoxyribonucleic acid
DSCI	Drought Severity and Coverage Index
EEA	European Environment Agency
ECDC	European Center for Disease Control
EPA	U.S. Environmental Protection Agency
FAO	Food and Agriculture Organization
HIV	Human Immunodeficiency Virus
iMOVES	international MObility of Veterinary Students
IRA	Inflation Reduction Act
PM_{10}	Particulate Matter $\leq$10 microns (coarse particulate matter)
$PM_{2.5}$	Particulate Matter $\leq$2.5 microns (fine particulate matter)
PRB	Po River Basin
PTSD	Post-Traumatic Stress Disorder
SME	Subject Matter Expert
SPEI	Standardized Precipitation and Evapotranspiration Index
SPI	Standardized Precipitation Index

TWS	GRACE Total Water Storage
TWSA	GRACE Total Water Storage Anomaly
WAL	Water Abstraction License
WHO	World Health Organization
WNV	West Nile Virus

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Dedication

This thesis is dedicated to the indigenous tribes of the Colorado River Basin for their perseverance in advocating for the health of the basin and continued effort to obtain water rights despite centuries of oppression.

Chapter 1 - Introduction

Climate Change

Global climate change threatens a variety of environmental resources including water. Rising temperatures and altered weather patterns affect the volume of existing surface and groundwater and precipitation. Evapotranspiration increases with higher temperatures, accelerating the global water cycle.[1] The accelerated water cycle increases precipitation and weather variability. Globally, climate change is expected to increase freshwater resources due to increased precipitation, runoff, river discharge, and flooding.[2] In some regions, however, the increased weather variability compounded with higher temperatures will lead to periods of drought interspersed with flooding.[3]

Half the global population experiences water scarcity for at least part of the year.[4] As climate change continues, water availability will continue to decline, especially for those already living in water-scarce environments.[5] Water scarcity is associated with various negative health outcomes including food insecurity, malnutrition, and water- and vector-borne diseases. In addition to expanding the number of people experiencing water scarcity, climate change will intensify the above negative health outcomes, inflicting a dual burden.[6]

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[1] Mukherji et al., "Synthesis Report of the IPCC Sixth Assessment Report (AR6)."

[2] Oki and Kanae, "Global Hydrological Cycles and World Water Resources."

[3] Mukherji et al., "Synthesis Report of the IPCC Sixth Assessment Report (AR6)."

[4] Mukherji et al.

[5] Gosling and Arnell, "A Global Assessment of the Impact of Climate Change on Water Scarcity."

[6] Mukherji et al., "Synthesis Report of the IPCC Sixth Assessment Report (AR6)."

Droughts and Definitions

Droughts are difficult to define, and many definitions exist in the literature. In their review of drought concepts, Mishra and Singh present several available definitions of drought and divide them into four groups, meteorological drought, hydrological drought, agricultural drought, and socioeconomic drought.[7] Mishra and Singh define meteorological drought as "a lack of precipitation over a region for a period of time," hydrological drought as "a period with inadequate surface and subsurface water resources for established water uses," agricultural drought as "a period with declining soil moisture and consequent crop failure," and socioeconomic drought as a "failure of water resources systems to meet water demands." Combining these definitions, drought can thus be defined as a temporary decline of precipitation, water resources, and soil moisture resulting in inadequate water availability accompanied by high temperatures. While low water availability is a defining characteristic of drought, drought-stricken areas also experience periodic flooding due to low soil permeability. Low precipitation and water availability, high temperatures, and cyclic drying and flooding thus define drought.

As with drought definitions, there are numerous, accepted ways to measure drought severity.[8] Drought indices may use meteorology (e.g., precipitation), soil moisture, hydrology (e.g., snowpack), or remote sensing data as input variables. Some indices, such as the Standardized Precipitation Index (SPI), make use of only one input variable. In contrast, others, such as the Standardized Precipitation and Evapotranspiration Index (SPEI) or the Drought Severity and Coverage Index (DSCI), use multiple variables and data types.

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[7] Mishra and Singh, "A Review of Drought Concepts." p. 206.

[8] In their 2016 "Handbook of Drought Indicators and Indices" published by the *Drought Mitigation Center*, Svoboda and Fuchs describe over 50 indices used to measure droughts.

Study Areas

This thesis will examine the drought conditions and associated health outcomes of two regions, the Po River Basin (PRB) in Northern Italy and the Colorado River Basin (CRB) in the Western United States. The 661-km (410-mi) Po River forms the 71,000 km^2 (27,000 mi^2) Po River Basin, providing water for 17 million people in Italy and Switzerland (Figure 1-1). The 2,220-km (1,400-mi) Colorado River forms the 630,000 km^2 (240,000 mi^2) Colorado River Basin, providing water for 40 million people across 7 states (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming), 30 federally recognized Tribes, and Mexico (Figure 1-2).[9] Both rivers are largely sourced from snowmelt, and as such are threatened by rising temperatures due to climate change. In the PRB, decreased precipitation and snowmelt and increased evapotranspiration (likely due to higher temperatures) have led to periodic drought conditions. Similarly, warming trends in the CRB have decreased snowpack leading to a sustained drought since 2000.

[9] The tribes of the Colorado River basin are the Ak-Chin Indian Community, Chemehuevi Indian Tribe, Cocopah Indian Tribe, Colorado River Indian Tribes, Fort McDowell Yavapi Nation, Fort Mojave Indian Tribe, Fort Yuma Quechan Indian Tribe, Gila River Indian Community, Havasupai Tribe, Hopi Tribe, Hualapai Indian Tribe, Jicarilla Apache Nation, Kaibab Band of Paiute Indians, Las Vegas Tribe of Paiute Indians, Moapa Band of Paiute Indians, Navajo Nation, Paiute Indian Tribe of Utah, Pascua Yaqui Tribe, Pueblo of Zuni, Salt River Pima-Maricopa Indian Community, San Carlos Apache Tribe, San Juan Southern Paiute Tribe, Southern Ute Indian Tribe, Tohono O'odham Nation, Tonto Apache Tribe, Ute Mountain Ute Tribe, Ute Indian Tribe, White Mountain Apache Tribe, Yavapai-Apache Nation, and Yavapai-Prescott Indian Tribe.

Figure 1-1; The Po River Basin.

Data source: Food and Agriculture Organization (FAO) and Esri

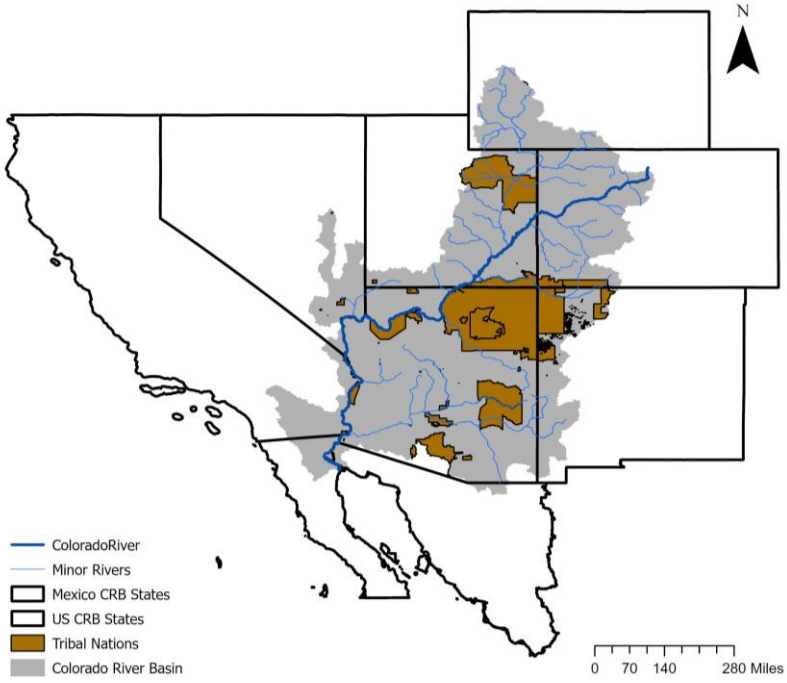

Figure 1-2; The Colorado River Basin.

Data source: The Lincoln Institute for Land Policy

While both the PRB and the CRB are currently experiencing drought conditions, the two regions have unique trajectories in a changing climate. Assuming consistent greenhouse gas emissions and low population and economic growth, water scarcity is predicted to be low to moderate in the PRB by 2050 but will increase due to lower snowpack volume, increased evapotranspiration, and decreased groundwater availability.[10] In the CRB, water scarcity is expected to be moderate to severe.[11] Beyond 2050, however, it is less clear. Some climate models show the CRB will receive more precipitation, reducing water scarcity, and others predict decreases in precipitation, resulting in increased water scarcity.[12] All models agree, however, that temperatures will continue to increase in the CRB.[13]

Despite present and predicted drought conditions, the Po and Colorado Rivers provide 16 and 14 million acre-feet of water per year, respectively.[14] Agriculture represents a significant portion of both rivers' water allocations. In the PRB, agriculture consumes 41% of allocated water, and agriculture consumes 70% of water allocated from the Colorado River, irrigating approximately 5.5 million acres of cropland.

Due to decreasing water availability, both the CRB and PRB require complex systems of water allocation. The 1922 Colorado River Compact largely regulates CRB allocations, building on the original "first in time, first in place" framework. The Compact divides the CRB into two halves, the Upper Basin comprising Utah, Colorado, Wyoming, and New Mexico, and the Lower

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[10] Alcamo, Florke, and Marker, "Future Long-Term Changes in Global Water Resources Driven by Socio-Economic and Climatic Changes."

[11] Alcamo, Florke, and Marker.

[12] Alcamo, Florke, and Marker.

[13] Alcamo, Florke, and Marker.

[14] Santato, Mysiak, and Pérez-Blanco, "The Water Abstraction License Regime in Italy." An acre-foot of water is equivalent to 325,850 gallons, approximately the amount of water in an 8-lane swimming pool or that used by a 4-to-5-person family in a year.

Basin comprising California, Arizona, and Nevada. Each basin is allocated 7.5 million acre-feet of water per year. Later legislation further defined each member state's annual allocation as shown in Table 1-1. The states within each basin then allocate water based on state and local legislation. Historically, the U.S. and CRB states denied tribal groups' water rights. The 1922 Compact failed to quantify allocations of the Colorado River to any tribe, despite the Supreme Court ruling in 1908's *Winters v. United States* that established Indigenous water rights as the oldest, and most senior, in the CRB.[15] Such water rights remained unrecognized until 1963's *Arizona v. California*; however, only 22 of the 30 tribes have a quantified water right today.

Table 1-1; Colorado River allocations by state.

	State	Annual Allocation (% of 7.5 million acre-feet)
Upper Basin	Colorado	51.75
	Utah	23.00
	Wyoming	14.00
	New Mexico	11.25
Lower Basin	California	58.67
	Arizona	37.33
	Nevada	4.00

In the PRB, Royal Decree No. 1775 of 1933 regulates water allocation.[16] According to the decree, only those with a Water Abstraction License (WAL) are permitted to draw water

[15] McKinney, Weiner, and Vigil, "First in Time."

[16] Santato, Mysiak, and Pérez-Blanco, "The Water Abstraction License Regime in Italy."

from the Po apart from water for domestic use.[17] Licenses are distributed by the Public Works Office and water drawing limits are set by regional governments.

Table 1-2; Characteristics of the Colorado River Basin and the Po River Basin.

	Colorado River Basin (CRB)	Po River Basin (PRB)
River Length (km)	2,220	661
Basin Area (km^2)	630,000	71,000
Population (millions)	40	17
Population Density (inhabitants/km^2)	63.5	239.4
Primary Water Source	Snowmelt	Snowmelt
Proportion Used for Agriculture	70%	40%
Legislative Framework	The 1922 Colorado River Compact	The 1933 Royal Decree nº 1775

In July 2023, the author observed the PRB as a part of the 2023 international MObility of Veterinary Students (iMOVES) program. The Po River had previously dropped to record low water levels in the summer of 2022, and in the spring of 2023 experienced severe flooding. By the time the author visited in the early summer of 2023, the Po had receded to normal levels. The author also interacted with the rich water-related history of the region, such as in the ruins of Brescia, a first-century Roman city above which the modern city is built. There, remains of *domus*, Roman houses, preserve ancient relationships with the PRB and public health

[17] Santato, Mysiak, and Pérez-Blanco.

infrastructure. At the center of the *domus* atrium, an *impluvium* collected rainwater for the household. Wealthy residents also had direct connections to the city aqueduct while the general public accessed aqueduct-fed fountains throughout the city.[18] Both the *impluvium* and aqueduct provided a more dependable water supply in the ancient PRB. Ancient Brescians also benefitted from complex wastewater management. Within a *domus*, lead pipes delivered fresh aqueduct water throughout the home while adjacent terracotta pipes removed wastewater to a public sewer.

Figure 1-3; Water and wastewater systems of a Roman *domus*.

Research Question and Methods

This thesis project includes a review of relevant literature regarding the themes highlighted above, insightful observations from subject matter experts (SMEs), and a comparative analysis of drought-related health effects in the CRB and PRB. Additionally, the

[18] The Brescian aqueduct supplied water from springs in the nearby city of Lumezzane.

author draws on personal observations from the PRB and the CRB.[19] This work seeks to address the following research question (which includes some, but not all, of the above themes):

What is the most salient health-related challenge facing both the CRB and the PRB?

To answer this question, the author will systematically adhere to the following framework:

- Using such accepted measurement tools as the Standardized Precipitation and Evapotranspiration Index (SPEI) and the GRACE Total Water Storage Anomaly (TWSA), the author will consider the mathematical severity of the two basins' current drought conditions.
- Using publicly available data, the author will assess the degree to which a variety of health outcomes are related to the two basins' drought conditions.
- Using data related to poverty and other social determinants of health, the author will evaluate the types and numbers of communities already or soon-to-experience water severity.

By limiting the analysis to these domains of inquiry, the author will inductively observe and, based on those observations, propose an argument regarding "the most salient health-related challenge facing both the CRB and the PRB."

[19] While visiting Piacenza, Italy in 2023, the author personally observed the conditions of the Po River. At the time, the PRB had recently experienced severe flooding, particularly in the delta, resulting in infrastructure damage and several deaths. Piacenza, being further upstream, did not experience such severe flooding, but evidence of flooding remained. The author also observed the Baby MOSES flood control system of Chioggia designed to protect the city and Venetian Lagoon from Po floods. The MOSES and Baby MOSES systems will be discussed further in Chapter 5.

Anticipated benefits of the thesis

Given the scale of this thesis's topic (the numerous health-related consequences of drought), the author does not seek to capture the entirety of the issue's nuance nor offer a definitive solution; however, the author does aim to provide an initial assessment to serve as the foundation for future work. Moreover, such topics of this scale—often called "grand challenges"—benefit from inductive research methods due to their interdisciplinary nature.[20] By inductively assessing the health-related challenges of drought in both regions, the author will explore a multitude of topics from a variety of data sources and perspectives, ranging from the biological and climatological to the sociological and political. This methodology will not only enrich the topic with multidisciplinary views but also replicate the methodologies used by public health practitioners and policymakers.[21] Such professionals often do not have the time or resources to conduct deductive or experimental research but rather rely on gathering existing data and information and inductively assessing relevance. Inductive methods also provide a framework for transparently generating new hypotheses, policies, and theories, critical processes for future, deductive research. In addition, this thesis serves to educate the author, an aspiring public health scholar and practitioner. By following this inductive and interdisciplinary research path, the author will grow in breadth of awareness, develop critical thinking skills, practice data analysis and visualization, and experience, firsthand, conditions and infrastructure in both regions.

[20] Eisenhardt, Graebner, and Sonenshein, "From the Editors."

[21] Kastner, "Sanitary Related International Trade Disputes: A Multiple-Factor Analysis Based on Nineteenth-Century Precedents." p. 17

Thesis Structure

This thesis's structure mirrors the effort to ultimately argue the most salient health-related challenge facing both the PRB and the CRB. As the logical starting point, Chapter 2 explores the range of possible health-related consequences of drought as evidenced by existing primary and secondary literature. Chapter 3 then examines the specific climatic circumstances of each region through the use of accepted drought indices and socio-political reactions. Next, Chapter 4 evaluates the presence and severity of the health-related challenges identified in Chapter 2. Finally, in the last step of this inductive synthesis, Chapter 5 argues for the most salient challenge in each basin and discusses possible mitigation strategies.

Chapter 2 - Health-related Consequences of Drought

Air Quality

Air quality is a major environmental factor that affects both human and animal health. Common air pollutants that degrade air quality include particulate matter (coarse, fine, and ultrafine), ozone, nitrogen dioxide, and sulfur dioxide.[22] Particulate matter often contains additional, potentially hazardous components such as microbes and transition metals.[23] Agriculture, fossil fuel combustion, and soil resuspension generate these ambient, airborne pollutants.[24] Once inhaled, airborne pollutants—and associated microbial endotoxins—interact with mucosal barriers and immune cells, generating an inflammatory response.[25] Accompanying transition metals and other compounds cause further damage through oxidative stress.[26] Fine particulate matter ($PM_{2.5}$) may also contain mutagenic compounds, notably hydrocarbons, that damage DNA and induce further cellular stress.[27] Additionally, inhaled particulate matter overwhelms mucociliary function, leading to prolonged exposure and altered function.[28] Inflammation, oxidative stress, and mutagenicity contribute to the negative effects of airborne pollutants on human health.

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[22] Williams, "1 - An Introduction to Allergic Inflammation and the Innate Immune Sensing of Dangerous Ambient Pollutants by the Dendritic Cell."

[23] Li et al., "3 - Environmental Lung Injury and Pattern Recognition Receptors."

[24] Williams, "1 - An Introduction to Allergic Inflammation and the Innate Immune Sensing of Dangerous Ambient Pollutants by the Dendritic Cell"; Traversi, "Mutagenicity of PM2.5."

[25] Williams, "1 - An Introduction to Allergic Inflammation and the Innate Immune Sensing of Dangerous Ambient Pollutants by the Dendritic Cell"; Li et al., "3 - Environmental Lung Injury and Pattern Recognition Receptors."

[26] Li et al., "3 - Environmental Lung Injury and Pattern Recognition Receptors."

[27] Traversi, "Mutagenicity of PM2.5."

[28] Georas and Frampton, "7 - Particulate Matter and Oxidative Stress."

Air pollution causes numerous negative health effects. Exposure to airborne pollutants amplifies the risk of pediatric upper respiratory tract infection and increases the frequency and severity of respiratory symptoms in asthmatics.[29] While the respiratory tract is the first system exposed to airborne pollutants, particulate matter also damages other organ systems, especially the cardiovascular system. Several studies have shown increases in cardiovascular disease hospital admissions associated with air pollution.[30] Exposure to airborne pollutants also increases rates of diabetes mellitus and adverse birth outcomes.[31] Particulate matter and other air pollutants thus cause a wide range of negative health effects, especially diseases of the respiratory and cardiovascular systems.

Drought influences air pollutant dynamics in several ways. Drought inhibits the removal of airborne pollutants from the air via precipitation,[32] alters the generation rate of pollutants such as ozone,[33] and expands the time airborne particulates are suspended.[34] Dry conditions also favor wildfires and the resuspension of soil, both common sources of airborne pollutants.[35] These mechanisms increase concentrations of PM_{10} (coarse particulate matter), $PM_{2.5}$, and nitrogen oxide despite reductions in anthropogenic emissions.[36] Conversely, periods of high precipitation

[29] Li et al., "The Interactive Effects between Drought and Air Pollutants on Children's Upper Respiratory Tract Infection"; Magnan et al., "4 - Asthma Exacerbations."

[30] Lippmann, "Ambient Air Partiuclate Matter."

[31] Feng et al., "The Health Effects of Ambient PM2.5 and Potential Mechanisms."

[32] This process is called "wet scavenging."

[33] Higher temperatures that accompany drought favor the chemical transformation of atmospheric oxygen to ozone.

[34] Wang et al., "Adverse Effects of Increasing Drought on Air Quality via Natural Processes."

[35] Bo et al., "Urban Air Pollution, Climate Change and Wildfires"; Šmejkalová and Brzezina, "The Effect of Drought on PM Concentrations in the Czech Republic."

[36] Hu et al., "Impact of Winter Droughts on Air Pollution over Southwest China."

reduce concentrations of PM_{10}.[37] Through these reductions in wet scavenging and changes in pollutant dynamics, drought worsens air quality.

Reductions in air quality pose wide-ranging health consequences and drought can exacerbate existing air-quality-related challenges. In addition to the negative health effects of air pollution discussed above, drought-associated elevations in $PM_{2.5}$ concentrations increase all-cause daily mortality, especially in the elderly.[38] Similarly, drought increases respiratory- and circulatory-related mortality. [39] The negative health consequences of air pollutants are exacerbated by drought conditions and exemplify the direct health consequences of drought.

Coccidioidomycosis (Valley Fever)

Particulate matter often includes soil-residing pathogens such as *Coccidioides immitis* and *C. posadasii*, the causative agents of coccidioidomycosis—also called Valley Fever after California's San Joaquin Valley. *Coccidioides* mycelia reside in the soil, producing spores that when inhaled cause fungal pneumonia in a variety of hosts (e.g., humans, dogs, aquatic mammals).[40] Soil moisture provided by winter precipitation and El Niño Southern Oscillations

[37] Baltaci et al., "The Influence of Meteorological Conditions and Atmospheric Circulation Types on PM10 Levels in Western Turkey."

[38] Fenech et al., "Meteorological Drivers and Mortality Associated with O3 and PM2.5 Air Pollution Episodes in the UK in 2006"; Salvador et al., "Effects of Drought on Mortality in Macro Urban Areas of Brazil Between 2000 and 2019."

[39] Fischer, Brunekreef, and Lebret, "Air Pollution Related Deaths during the 2003 Heat Wave in the Netherlands"; Salvador et al., "Drought Effects on Specific-Cause Mortality in Lisbon from 1983 to 2016"; Salvador et al., "Short-Term Effects of Drought on Daily Mortality in Spain from 2000 to 2009."

[40] Nguyen et al., "Recent Advances in Our Understanding of the Environmental, Epidemiological, Immunological, and Clinical Dimensions of Coccidioidomycosis."

facilitates the growth of *Coccidioides* mycelia.[41] Proceeding periods of high temperatures and drought then dry the soil, increasing the risk of soil disturbance.[42] Activities that disturb soil containing *Coccidioides* spores—such as vehicular traffic, construction, or agriculture—facilitate the transmission of Valley Fever to humans.[43] Thus, within-year variability of precipitation increases the transmission of Valley Fever, contributing to the public health burden of drought-related air pollution.[44]

Water Safety

In addition to reducing soil moisture, drought alters surface water availability, increasing risks of chemical and microbial contamination. Droughts reduce surface water availability while also increasing the risk of severe flooding events. These drought-associated floods—called drought-flood abrupt alternations (DFAAs)—introduce non-point source nitrogen and phosphorus pollution (likely from agricultural activity) via runoff.[45] Similarly, groundwater depletion during droughts increases nitrate concentrations in private wells, critical water infrastructure in rural communities.[46] This nitrate contamination can result in inadequate blood

[41] Tobin, Pokharel, and Bennett, "Coccidioidomycosis (Valley Fever), Soil Moisture, and El Nino Southern Oscillation in California and Arizona"; Weaver and Kolivras, "Investigating the Relationship Between Climate and Valley Fever (Coccidioidomycosis)."

[42] Head et al., "Effects of Precipitation, Heat, and Drought on Incidence and Expansion of Coccidioidomycosis in Western USA."

[43] Lauer et al., "Valley Fever."

[44] Shriber et al., "Assessment of Vulnerability to Coccidioidomycosis in Arizona and California."

[45] Bi et al., "Evolution of Drought–Flood Abrupt Alternation and Its Impacts on Surface Water Quality from 2020 to 2050 in the Luanhe River Basin."

[46] Levy et al., "Critical Aquifer Overdraft Accelerates Degradation of Groundwater Quality in California's Central Valley During Drought."

oxygenation levels in infants and occasionally fatal methemoglobinemia.[47] DFAAs also increase exposure to a variety of microbial contaminants. Runoff from surrounding areas carries bacteria (e.g., coliform bacteria) and parasites (e.g., *Giardia* and *Cryptosporidium*) to nearby reservoirs, threatening municipal water supplies.[48] In urban areas, floodwaters often overflow and overwhelm sewer and stormwater systems, exposing residents to bacterial, parasitic, and viral (e.g., enteroviruses) threats.[49] Municipal water management strategies enacted during droughts also introduce water safety hazards. Common strategies to ensure water access including intermittent water supply, water source blending, and bulk water distribution contaminate water by flushing mineral deposits in stagnant pipes.[50] Microbial contaminants, such as bacterial biofilms, also contaminate water in this way.[51] Reduced, often stagnant surface water also increases risks of microbial contamination by concentrating and amplifying microbial populations. Cholera, for example, can increase during drought due to an increased abundance of reservoir hosts (e.g., algae and zooplankton).[52] Through changes in ecology and infrastructure, drought introduces chemical and biological contamination and reduces water quality.

Mosquito-borne Diseases

Drought-driven declines in surface water availability impact the ecology and epidemiology of mosquito-borne diseases as abundant water resources are necessary for

[47] Maxwell, *Understanding Environmental Health: How We Live in the World*.

[48] Kistemann et al., "Microbial Load of Drinking Water Reservoir Tributaries during Extreme Rainfall and Runoff."

[49] de Man et al., "Quantitative Assessment of Infection Risk from Exposure to Waterborne Pathogens in Urban Floodwater."

[50] Salehi, "Global Water Shortage and Potable Water Safety; Today's Concern and Tomorrow's Crisis."

[51] Salehi.

[52] Charnley, Kelman, and Murray, "Drought-Related Cholera Outbreaks in Africa and the Implications for Climate Change."

mosquito populations at all phases of their life cycles. Adult mosquitoes require water to balance metabolites and lay eggs, and mosquito larvae require water to develop. Although counterintuitive, drought can increase mosquito abundance and consequently amplify the burden of mosquito-borne diseases.

Mosquitoes have evolved several strategies to cope with drought and consequent dehydration. In *Anopheles* species, the 2La chromosomal inversion protects against water loss.[53] Melanin protects eggs from desiccation after removal from water in *Anopheles, Aedes, and Culex* species.[54] The most effective mechanism for dehydration tolerance in some mosquito species is diapause, a programmed process for temporarily delaying development and restricting metabolism.[55] Diapause reduces water loss in mosquitoes by reducing metabolic activity, suppressing lipid oxidation, increasing body size (a larger body size creates a lower surface area to volume ratio rendering water loss proportionally less significant), producing extra-cuticular hydrocarbons, and down-regulating aquaporin expression.[56] Diapause, in conjunction with other shared strategies, confers resistance to dehydration in mosquitoes.

In addition to dehydration resistance strategies, *Culex* mosquitoes display altered behavior in drought conditions. *Culex* mosquitoes are generally more active in dry months than

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[53] Reidenbach et al., "Cuticular Differences Associated with Aridity Acclimation in African Malaria Vectors Carrying Alternative Arrangements of Inversion 2La."

[54] Farnesi et al., "Darker Eggs of Mosquitoes Resist More to Dry Conditions."

[55] Rinehart, Robich, and Denlinger, "Enhanced Cold and Desiccation Tolerance in Diapausing Adults of Culex Pipiens, and a Role for Hsp70 in Response to Cold Shock but Not as a Component of the Diapause Program"; Denlinger and Armbruster, "Mosquito Diapause."

[56] Benoit and Denlinger, "Suppression of Water Loss during Adult Diapause in the Northern House Mosquito, Culex Pipiens"; Yang, Denlinger, and Piermarini, "The Diapause Program Impacts Renal Excretion and Molecular Expression of Aquaporins in the Northern House Mosquito, Culex Pipiens." Aquaporins are highly conserved transporters that expel water to maintain osmotic balance.

Anopheles or *Aedes* species, and following droughts, *Culex pipiens* (*C. pipiens*) abundance increases in semi-permanent wetlands.[57] Dehydration in *Culex* mosquitoes increases activity and biting rates, amplifying the risk of disease transmission.[58] These behaviors differentiate *Culex* mosquitoes from other vectors and facilitate the amplification of diseases vectored by *Culex* mosquitoes in drought conditions.

The most well-evidenced zoonotic disease associated with drought is West Nile Virus (WNV). *C. pipiens*, the main WNV vector in the United States and Italy, has a higher dehydration tolerance than most insects, including other mosquitoes, as they are capable of tolerating up to 40% water loss.[59] In addition to the drought resilience strategies discussed above, vector-pathogen dynamics facilitate the relationship between WNV and drought. Higher temperatures that often accompany drought increase WNV titers in mosquitoes, shorten mosquito infection time, and increase the amount of virus transmitted from vectors to hosts.[60] Similarly, higher temperatures increase mosquito WNV infection rates.[61] High temperatures also act as an additional evolutionary pressure and have a differential and selective effect on WNV strains.[62] Combined with the dehydration resistance strategies and drought behavior of the *Culex*

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[57] Benoit and Denlinger, "Suppression of Water Loss during Adult Diapause in the Northern House Mosquito, Culex Pipiens"; Chase and Knight, "Drought-Induced Mosquito Outbreaks in Wetlands."

[58] Hagan et al., "Dehydration Prompts Increased Activity and Blood Feeding by Mosquitoes."

[59] Benoit and Denlinger, "Suppression of Water Loss during Adult Diapause in the Northern House Mosquito, Culex Pipiens." *Anopheles arabiensis* and *A. gambiae* can tolerate up to 29% and 33% loss, respectively. Few insects can tolerate beyond 70% water loss.

[60] Reisen, Fang, and Martinez, "Effects of Temperature on the Transmission of West Nile Virus by Culex Tarsalis (Diptera."

[61] Kilpatrick et al., "Temperature, Viral Genetics, and the Transmission of West Nile Virus by Culex Pipiens Mosquitoes."

[62] Kilpatrick et al.

vector, WNV dynamics during drought facilitate the relationship between WNV transmission and drought.

Although indirect, the association between WNV incidence and drought is well-evidenced in both mosquito and human populations. Mosquito infection rates are higher in mosquitoes incubated at higher temperatures, and higher temperatures facilitate faster within-vector dissemination of WNV.[63] Similarly, WNV infections increase in *C. pipiens* and *C. tarsalis* following drought, independent of mosquito abundance.[64] In natural environments, mosquito WNV incidence increases in dry summers when preceded by high winter and spring precipitation.[65] In the United States, drought can potentially double the WNV burden, particularly in populations without prior immunity.[66] The effect of drought on WNV in human populations is difficult to measure due to the indirect nature of the association and the temporal scale at which the effect occurs. Higher average yearly temperature and lower precipitation are associated with increased WNV cases.[67] However, these coarse associations are not consistent across different years or geographic areas.[68] Temperature and precipitation fluctuations within a

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[63] Dohm, O'Guinn, and Turell, "Effect of Environmental Temperature on the Ability of Culex Pipiens (Diptera."

[64] Paull et al., "Drought and Immunity Determine the Intensity of West Nile Virus Epidemics and Climate Change Impacts."

[65] Shaman, Harding, and Campbell, "Meteorological and Hydrological Influences on the Spatial and Temporal Prevalence of West Nile Virus in Culex Mosquitoes, Suffolk County, New York."

[66] Paull et al., "Drought and Immunity Determine the Intensity of West Nile Virus Epidemics and Climate Change Impacts."

[67] Johnson and Sukhdeo, "Drought-Induced Amplification of Local and Regional West Nile Virus Infection Rates in New Jersey"; Davis et al., "Improving the Prediction of Arbovirus Outbreaks"; Ruiz et al., "Local Impact of Temperature and Precipitation on West Nile Virus Infection in Culex Species Mosquitoes in Northeast Illinois, USA"; Wang et al., "A Compound Cloud Model for Harmoniousness Assessment of Water Allocation."

[68] Johnson and Sukhdeo, "Drought-Induced Amplification of Local and Regional West Nile Virus Infection Rates in New Jersey"; Davis et al., "Improving the Prediction of Arbovirus Outbreaks"; Ruiz et al., "Local Impact of

year are more strongly associated with WNV incidence. Winter precipitation is a strong predictor of higher WNV incidence in the following summer in the U.S. and Italy. [69] Spring precipitation, however, is the most commonly associated factor for WNV incidence.[70] Spring precipitation likely increases WNV incidence by providing early habitat for mosquito populations, increasing vector abundance.[71] Following spring precipitation, warm and dry conditions in the late summer restrict surface water availability, reducing predator and competitor populations and encouraging congregation of vectors and potential hosts.[72] At the end of these summer drought conditions, late precipitation facilitates the dispersion of infected avian hosts, extending the transmission season.[73] Thus, within-year cycles of wetting, drought, and re-wetting emerge as a critical factor for WNV transmission in mosquito, avian, and human populations.

Temperature and Precipitation on West Nile Virus Infection in Culex Species Mosquitoes in Northeast Illinois, USA."

[69] Wimberly et al., "Regional Variation of Climatic Influences on West Nile Virus Outbreaks in the United States"; Shaman, Day, and Komar, "Hydrologic Conditions Describe West Nile Virus Risk in Colorado"; Marcantonio et al., "Identifying the Environmental Conditions Favouring West Nile Virus Outbreaks in Europe."

[70] Wimberly et al., "Regional Variation of Climatic Influences on West Nile Virus Outbreaks in the United States"; Ukawuba and Shaman, "Association of Spring-Summer Hydrology and Meteorology with Human West Nile Virus Infection in West Texas, USA, 2002–2016"; Rosà et al., "Early Warning of West Nile Virus Mosquito Vector"; Shaman, Day, and Komar, "Hydrologic Conditions Describe West Nile Virus Risk in Colorado"; Shaman, Harding, and Campbell, "Meteorological and Hydrological Influences on the Spatial and Temporal Prevalence of West Nile Virus in Culex Mosquitoes, Suffolk County, New York"; Carrieri et al., "Weather Factors Influencing the Population Dynamics of Culex Pipiens (Diptera."

[71] Rosà et al., "Early Warning of West Nile Virus Mosquito Vector."

[72] Chase and Knight, "Drought-Induced Mosquito Outbreaks in Wetlands"; Shaman, Harding, and Campbell, "Meteorological and Hydrological Influences on the Spatial and Temporal Prevalence of West Nile Virus in Culex Mosquitoes, Suffolk County, New York."

[73] Rosà et al., "Early Warning of West Nile Virus Mosquito Vector"; Shaman, Harding, and Campbell, "Meteorological and Hydrological Influences on the Spatial and Temporal Prevalence of West Nile Virus in Culex Mosquitoes, Suffolk County, New York."

Malnutrition

Drought also worsens several social and economic determinants of health including nutrition. Many agricultural communities depend on locally cultivated crops and livestock for nutritional content. When drought decreases crop yields, subsistence agriculturists face food insecurity.[74] Decreased water availability also inhibits food preparation and safety while diverting income from food acquisition to water acquisition.[75] Through these mechanisms, drought increases short-term effects of malnutrition such as lower body mass, especially in children.[76] Long-term effects, such as child wasting or stunting, may also increase following drought periods, but this effect is contested.[77] While drought is often not the sole contributor to food insecurity, especially in poor communities, it does exacerbate existing challenges.

Migration

Drought poses numerous health-related and economic challenges that often induce internal (within-country) and external (between-country) migration. Drought-related migration typically consists of men from rural, agricultural communities seeking alternate income in urban areas.[78] Migration as an adaptive strategy, however, is often a temporary last resort.[79] Despite

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[74] Lieber et al., "A Systematic Review and Meta-Analysis Assessing the Impact of Droughts, Flooding, and Climate Variability on Malnutrition"; Brewis et al., "Household Water Insecurity Is Strongly Associated with Food Insecurity."

[75] Brewis et al., "Household Water Insecurity Is Strongly Associated with Food Insecurity."

[76] Lieber et al., "A Systematic Review and Meta-Analysis Assessing the Impact of Droughts, Flooding, and Climate Variability on Malnutrition"; Jankowska et al., "Climate Change and Human Health."

[77] Jankowska et al., "Climate Change and Human Health"; Hagos et al., "Climate Change, Crop Production and Child under Nutrition in Ethiopia; a Longitudinal Panel Study"; Yeboah et al., "Every Drop Matters."

[78] Gray and Mueller, "Drought and Population Mobility in Rural Ethiopia"; Defrance, Delesalle, and Gubert, "Migration Response to Drought in Mali. An Analysis Using Panel Data on Malian Localities over the 1987-2009 Period."

these extreme circumstances, drought-related migration is a critical contributor to global migration, accounting for 10% of the global increase in migration between 1970 and 2000.[80] Some sub-populations—notably women and the poor—are unable to migrate due to financial or other barriers and instead face other health-related challenges of drought.[81] Those who do migrate also experience a variety of negative health outcomes. Common migration destinations, nearby cities, also experience drought risks (e.g., water shortages) and may be unprepared for a population influx.[82] Migrants, when not appropriately supported by the nation-state governments receiving them, face an increased risk of a variety of infectious diseases—tuberculosis, HIV/AIDs, and water- and food-borne illnesses.[83] Mental health challenges including PTSD, schizophrenia, and depression also persist in migrant communities and are discussed further in the next section.[84] Furthermore, the act of migration poses severe biosecurity risks by facilitating the geographic spread of pathogens.[85] Migration is often the final adaptive strategy for rural agriculturists during drought; however, migration intensifies many of the health-related consequences of drought.

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[79] Jülich, "Drought Triggered Temporary Migration in an East Indian Village."

[80] Zaveri et al., *Ebb and Flow*. Drought is also 5 times more likely to result in migration than flooding events.

[81] Gray and Mueller, "Drought and Population Mobility in Rural Ethiopia"; Zaveri et al., *Ebb and Flow*; Defrance, Delesalle, and Gubert, "Migration Response to Drought in Mali. An Analysis Using Panel Data on Malian Localities over the 1987-2009 Period."

[82] Zaveri et al., *Ebb and Flow*.

[83] Gushulak and MacPherson, "Migration in a Mobile World: Health, Population Mobility, and Emerging Disease."

[84] Bhugra, "Migration and Mental Health."

[85] Gushulak and MacPherson, "Migration in a Mobile World: Health, Population Mobility, and Emerging Disease."

Mental Health

Drought also impacts the mental health of affected communities. Food insecurity, as previously discussed, is one consequence of drought and is closely related to mental distress.[86] Other stressors, including financial distress and social isolation, add to the mental burden of rural communities during drought.[87] Farmers and their families thus report increased stress and depression during droughts.[88] Drought-related mental health challenges can be so severe to increase suicides in men living in rural communities.[89] These challenges are unique to rural communities that have more financial and emotional stake in environmental, crop, and livestock health.[90] The culminating economic and health-related challenges of drought have severe consequences on rural mental health, compounding the public health burden.

Discussion

Drought directly and indirectly affects human health through a variety of means. Decreased soil moisture facilitates the aerosolization of particulate matter that induces inflammation and oxidative stress while potentially exposing hosts to pathogens such as *Coccidioides*. Decreased water availability reduces hygiene and provides an opportunity for chemical and microbial contamination. Related ecological changes amplify the transmission of mosquito-borne diseases such as West Nile Virus. The conjunction of decreased soil moisture

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[86] Friel et al., "The Impact of Drought on the Association between Food Security and Mental Health in a Nationally Representative Australian Sample."

[87] Vins et al., "The Mental Health Outcomes of Drought"; Sartore et al., "Control, Uncertainty, and Expectations for the Future."

[88] Vins et al., "The Mental Health Outcomes of Drought"; Sartore et al., "Control, Uncertainty, and Expectations for the Future"; Dean and Stain, "Mental Health Impact for Adolescents Living with Prolonged Drought."

[89] Hanigan and Chaston, "Climate Change, Drought and Rural Suicide in New South Wales, Australia."

[90] OBrien et al., "Drought as a Mental Health Exposure."

and water availability increases crop failures, inducing malnutrition in subsistence communities. Residents of these rural communities often migrate to cities in search of alternate income sources, exposing them to increased risk of infectious disease and facilitating the geographic spread of pathogens. Finally, all the above consequences, in addition to economic challenges, exacerbate the mental health of rural communities resulting in increased anxiety, depression, and deaths by suicide. Figure 2-1 shows the relationship between drought effects and the above public health concerns.

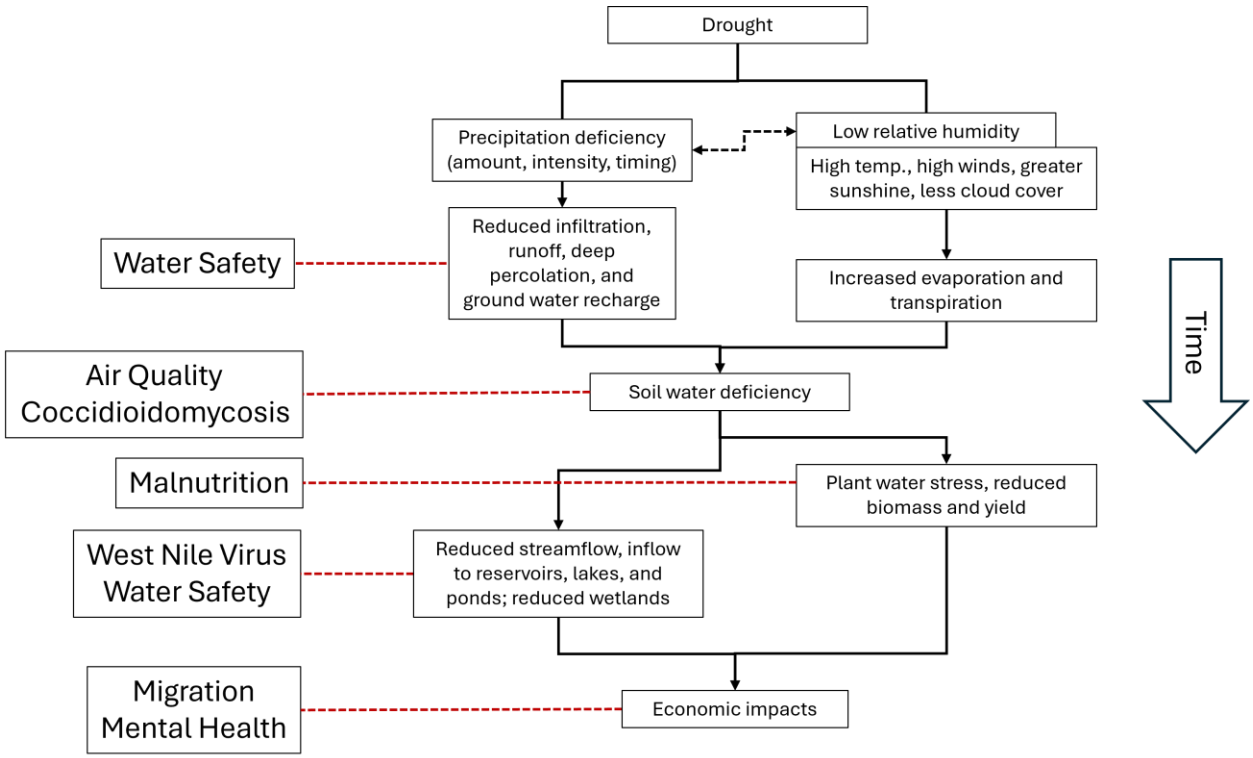

Figure 2-1; Health-related effects of drought.

Adapted from Zargar et al., 2010.[91]

Together, the health-related consequences of drought burden global and local public health systems. As climate change accelerates the global water cycle, droughts and associated

[91] Zargar et al., "A Review of Drought Indices."

health challenges will become more common. Given the wide range of potential health-related consequences, public health practitioners must understand the unique climatic variables of their surrounding ecology and identify the most salient challenges in their communities to better target public health surveillance and intervention.

Chapter 3 - Drought in the Colorado and Po River Basins

Both Italian and U.S. observers have rightly expressed alarm over the drought events of the past decade. National and international attention has focused on the historic drought conditions in the PRB and CRB, especially regional impacts on agriculture, energy generation, economies, and government response. Both regions have experienced historic droughts in recent years as the Po and Colorado rivers and associated lakes and reservoirs reached record lows. In each case, these record lows revealed lost artifacts of World War II, an Italian barge named *Zibello* and an American landing craft (figure 3-1).[92] Such relicts evidence recent declines of the Po and Colorado rivers as well as the Po's Lake Garda and the Colorado's Lake Powell and Lake Mead. 2022 flow rates at the Po Delta were just 10% of annual averages while Lake Garda dropped to 31.7% of its total volume.[93] Similarly, the Colorado River's average annual flow has declined to 66% of normal volumes while Lakes Mead and Powell fell to 25% of their total volume.[94]

Figure 3-1; The *Zibello*, an Italian WWII supply barge, (left) and an American WWII landing craft (right).

[92] CBS News, "Italy's Largest River Dries up, Exposing World War II Barge That Sank in 1943"; Cullinane, "Drought-Stricken Lake Mead Recedes to Reveal a World War II-Era Landing Craft."

[93] Navarra and Bruno, "Italy's Salty Po Delta Hurting Agriculture, Fisheries"; ANSA, "Drought," April 21, 2023.

[94] Karlamangla, "How Colorado River Cuts Could Affect California"; Weise, "Lake Powell Hits Historic Low Levels: With Lake Mead, Holds Water for 40M in West."

As a result of low river and lake volumes, the PRB and CRB are at risk of energy shortages. The Po and Colorado rivers are critical sources of hydropower for their regions. In Italy, the Po sources 55% of the nation's hydropower, corresponding to approximately 11% of Italy's energy generation.[95] The 2022 drought in the PRB reduced hydropower capacity by 40%.[96] In the U.S., the Colorado sources 53% of the West's renewable energy, and hydropower accounts for 6% of U.S. energy production.[97] The two largest dams responsible for hydropower generation, Hoover Dam (which forms Lake Mead) and Glen Canyon Dam (which forms Lake Powell), are also experiencing reductions in energy generation due to the ongoing drought. Hoover Dam's energy generation has fallen by 30-40% over the past 10 years, and Glen Canyon Dam's energy generation has decreased by 45%.[98] Together, both Hoover and Glen Canyon supply energy to 6 million people in Arizona, Utah, New Mexico, California, and Nevada.[99] Glen Canyon Dam, however, is at a higher risk of failure as the level of Lake Powell in 2022 was just 44 feet higher than deadpool, the level at which water can no longer pass through the generator's turbines.[100] Thus, while hydropower is a more important energy source in the PRB, drought in the CRB presents a more urgent threat to the region.

Agriculture impacts are the most newsworthy consequence of drought in both the PRB and CRB. As discussed in Chapter 1, agriculture is the single largest industry that receives

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[95] CBS News, "Italy's Largest River Dries up, Exposing World War II Barge That Sank in 1943"; "Drought Hits Italy's Hydroelectric Plants."

[96] "Drought Hits Italy's Hydroelectric Plants."

[97] Kelley, "Drought Threatens Colorado River Hydropower, Major Source of Renewable Energy."

[98] Ramirez, "The West's Historic Drought Is Threatening Hydropower at Hoover Dam"; Kelley, "Drought Threatens Colorado River Hydropower, Major Source of Renewable Energy."

[99] Ramirez, "The West's Historic Drought Is Threatening Hydropower at Hoover Dam"; Kelley, "Drought Threatens Colorado River Hydropower, Major Source of Renewable Energy."

[100] Ramirez, "The West's Historic Drought Is Threatening Hydropower at Hoover Dam."

allocations from the Po and Colorado rivers, and each region is responsible for a significant portion of their nation's agriculture. The PRB produces approximately 40% of Italy's food. Drought, however, threatens 30-40% of this production as yields have fallen by 15-45% for PRB products that include cereals (particularly rice), animal feed, shellfish, fruit, and milk.[101] The CRB is similarly critical to U.S. food supplies, producing 90% of the nation's winter vegetables in addition to animal feed and products. Drought has similarly strained agriculture in the CRB as farmers fallow 30-40% of their fields.[102] Reductions in agricultural yields in both regions have resulted in major economic losses. Over the past decade of drought in the PRB, the region experienced $14.5 billion of economic loss while the CRB also experienced multibillion-dollar losses.[103] Reduced agricultural production and resulting economic losses impact farmers and residents of both basins while also presenting a critical threat to national consumers and policymakers.

To mitigate economic losses and ensure adequate water supplies, local, regional, and federal governments have enacted several emergency and long-term policies. In Italy, 170 towns began rationing municipal water, allowing water use for only essential purposes (e.g., food preparation and drinking).[104] Some towns, however, have taken more extreme measures such as shutting off water supplies at night and banning barbershops and salons from double shampooing clients' hair.[105] Regional governments have also sought to limit agricultural irrigation by limiting

[101] CBS News, "Italy's Largest River Dries up, Exposing World War II Barge That Sank in 1943"; ANSA, "Drought," July 25, 2022.

[102] Loomis, "Water Reduction Hits Central Ariz. Growers."

[103] Raney, "The Region Responsible for 40% of Italy's Agriculture Faces Worst Drought in 70 Years."

[104] ANSA, "Drought," June 17, 2022.

[105] ANSA; Giuffrida, "Italian Hairdressers Face Fines for Shampooing amid Heatwave."

what crops may be irrigated.[106] More long-term solutions for Italians, however, are yet to be seen as the federal government only recently explored appointing a drought commissioner and investments in water infrastructure.[107] In the U.S., the federal government and individual states play much larger roles in investing in more long-term measures. For example, the recently passed Inflation Reduction Act (IRA) incentivizes water conservation by offering individuals and cities between $330 to $400 per acre-foot conserved.[108] In addition to water conservation incentives, lower basin states have agreed to reduce their allocations of the Colorado River, restricting the amount of water available to consumers and raising costs.[109] Past investments in large infrastructure projects by federal and state governments, such as the Central Arizona Project (CAP), have also provided drought resilience and relief. Although necessary, emergency and long-term government responses to droughts further challenge individuals and industry.

Holistically understanding the drought conditions for a region is the first step in identifying the most salient drought-related public health threats. As discussed in Chapter 2, public health threats are dependent on drought severity and longevity as shorter, mild droughts have a different influence on disease and human ecology than longer, more severe droughts. Thus, policymakers and public health practitioners must examine the hydrological conditions of the Po and Colorado River Basins to better understand the salient public health threats.

There are many means to define and measure droughts (as discussed in Chapter 1). For this thesis, the author considered the following criteria in determining which measure to use: data availability, comparability, complexity, and processing capacity. The ideal measure would use

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[106] Santalucia, "Rice Fields Dry up as Italy's Drought Lingers On."

[107] Fonte and Amante, "Italy to Appoint Drought Special Commissioner."

[108] Seely, "Arizona Cities Will Cut Back Water Use."

[109] Seely; Shinn, "Will Outdoor Irrigation Rules in Colorado Springs Tighten amid Drought Conditions?"; Scanlon, "Mesa Sees Water Cost Increases amid Drought."

data publically available for both the PRB and the CRB, consider multiple climate variables, and require computational power within the limits of the author's computer. Following these guidelines, the author selected the Standardized Precipitation and Evapotranspiration Index (SPEI) and the GRACE Total Water Storage Anomaly (TWSA).

SPEI is a recently developed drought measure, building on the pre-existing Standardized Precipitation Index (SPI). Whereas SPI relies only on precipitation data, SPEI also considers the amplifying effect of temperature on water availability.[110] Another strength of the SPEI is the variable timescales at which it may be calculated. When calculated at smaller timescales (e.g., 3 months), SPEI captures brief, less severe droughts, and when considering larger timescales (e.g., 18 months), SPEI measures severe, long-lasting droughts.[111] Table 3-1 summarizes the relationship between SPEI value and drought conditions. This dual consideration of the two most important climatic variables at varying timescales renders the SPEI a highly sensitive and robust measure of drought.

Similarly, the GRACE TWSA provides a holistic measure of drought conditions. GRACE TWS is a measure of the total surface and groundwater availability in a given area, calculated from differences in Earth's gravitational force as observed by the two GRACE-FO satellites.[112] Once monthly TWS values are calculated, they are transformed into TWSA values by comparison to the 2002–2022 mean value. The main strength of TWSA data is its ability to measure groundwater availability, proxying long-term hydrological drought.[113] Table 3-2 summarizes the relationship between TWSA and drought conditions. By using both SPEI and

[110] Vicente-Serrano, Beguería, and López-Moreno, "A Multiscalar Drought Index Sensitive to Global Warming."

[111] Vicente-Serrano, Beguería, and López-Moreno.

[112] Wahr et al., "Time-Variable Gravity from GRACE."

[113] Cammalleri, Barbosa, and Vogt, "Analysing the Relationship between Multiple-Timescale SPI and GRACE Terrestrial Water Storage in the Framework of Drought Monitoring."

TWSA, this study considered varying drought lengths and severity based on both surface and groundwater.

Table 3-1; SPEI values and their classifications.

SPEI Value	Classification
2.0 and above	Extremely wet
1.99 to 1.5	Very wet
1.49 to 1.0	Moderately wet
0.99 to -0.99	Normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Very dry
-2 and below	Extremely dry

Table 3-2; TWS values and their classifications.

TWS Value	Classification
1.0 and above	Wetter than normal
0.99 to -0.99	Near normal
-1.0 and below	Drier than normal

Methods: Data sets and analysis

SPEI Data. The author obtained monthly SPEI data from the Global SPEI Database at timescales of 3 months (SPEI-3), 18 months (SPEI-18), and 36 months (SPEI-36).[114] The author downloaded data for the center of the PRB (9.69 °E 45.17 °N), the center of the Lower CRB

[114] Vicente-Serrano, Beguería, and López-Moreno, "A Multiscalar Drought Index Sensitive to Global Warming."

(112.18 ˚W 34.37 ˚N), and the center of the Upper CRB (109.06 ˚W 39.06 ˚N) as only point data were available. Data consisted of monthly SPEI values from 1901 through 2022, but only values from 2012 through 2022 were considered.

TWSA Data. The author obtained TWSA data from the Global Drought Observatory (GDO) for January 2022 through September 2023.[115] Data consisted of raster files containing TWSA values for each month. ArcGIS Pro (version 3.2.1, Esri Inc.) calculated monthly average TWSA values for each basin.

Statistical Analysis. SPEI and Average TWSA descriptive statistics were calculated using R.[116] One-way ANOVAs and Scheffe post-hoc tests were used to compare SPEI and TWS data between the three basins. Data was visualized with the ggplot2 package in R Studio.[117]

Results and Discussion

SPEI-3. In the study period between 2012 and 2022, the PRB experienced an average 3-month SPEI of -0.2 (normal), ranging between -1.8 (very dry) and 1.7 (very wet). The Lower CRB experienced an average SPEI-3 of -0.3 (normal), ranging between -2.5 (extremely dry) and 1.4 (moderately wet), while the Upper CRB experienced an average SPEI-3 of -0.4 (normal), ranging between -2.5 (extremely dry) and 1.8 (very wet). Statistical testing failed to detect a significant difference in SPEI-3 values among each basin. Figure 3-1 summarizes the SPEI-3 results for each basin.

[115] Global Drought Observatory, "Data Download - Global Drought Observatory - JRC European Commission."

[116] R Core Team, "R: A Language and Environment for Statistical Computing."

[117] Wickham, *Ggplot2*.

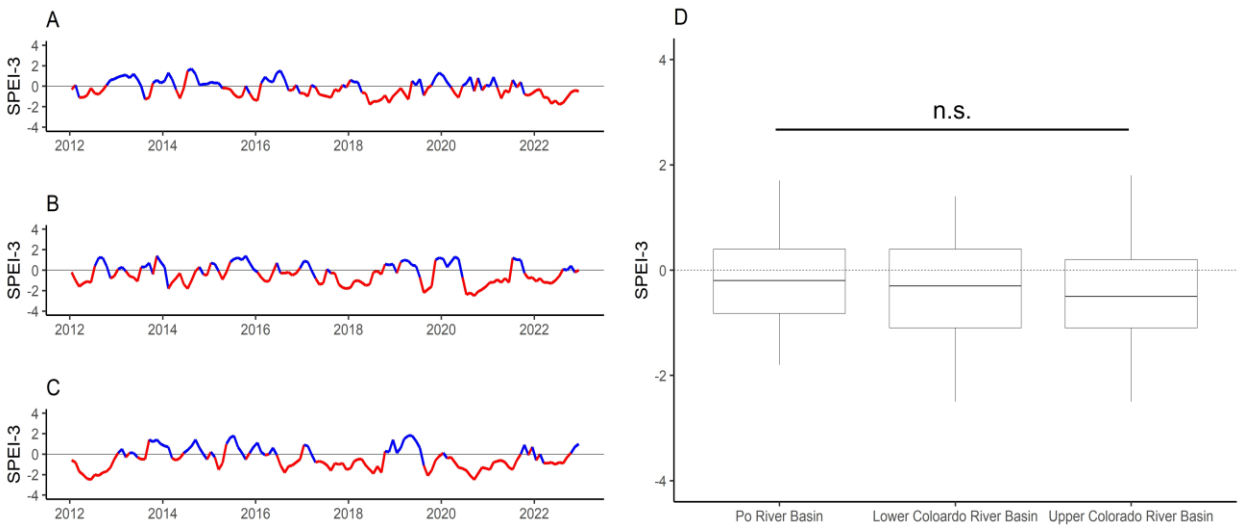

Figure 3-2; SPEI-3 from 2012 to 2022.

(A) SPEI-3 values from 2012 to 2022 in the PRB. (B) SPEI-3 values from 2012 to 2022 in the Lower CRB. (C) SPEI-3 values from 2012 to 2022 in the Upper CRB. (D) Comparison between SPEI-3 values from 2012 to 2022 across the PRB, Lower CRB, and Upper CRB.

SPEI-18. During the study period, the PRB experienced an average 18-month SPEI of -0.5 (normal), ranging between -1.9 (very dry) and 1.7 (very wet). The Lower CRB experienced an average SPEI-18 of -0.8 (normal), ranging between -2.3 (extremely dry) and 0.9 (normal), while the Upper CRB experienced an average SPEI-18 of -0.7 (normal), ranging between -2.2 (extremely dry) and 1.0 (moderately wet). Post-hoc testing revealed statistically significant differences in SPEI-18 values between the PRB and the Lower CRB (p-value = 0.0059) and the PRB and the Upper CRB (p-value = 0.028). Figure 3-2 summarizes the SPEI-18 results for each basin.

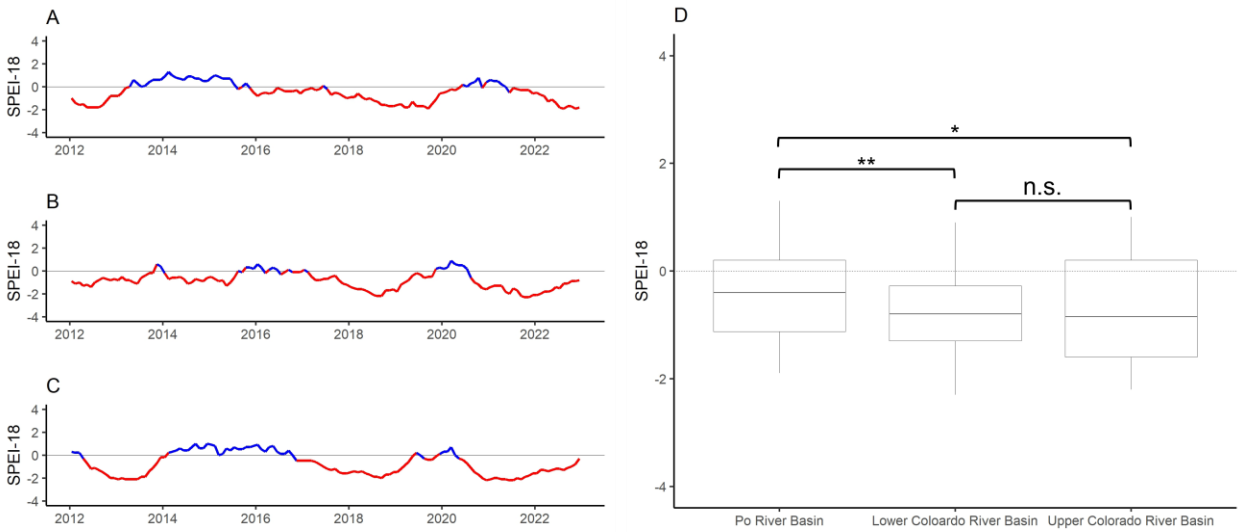

Figure 3-3; SPEI-18 from 2012 to 2022.

(A) SPEI-18 values in the PRB. (B) SPEI-18 values in the Lower CRB. (C) SPEI-18 values in the Upper CRB. (D) Comparison between SPEI-18 values across the PRB, Lower CRB, and Upper CRB.

SPEI-36. During the study period, the PRB experienced an average 36-month SPEI of -0.6 (normal), ranging between -1.7 (very dry) and 0.8 (normal). The Lower CRB experienced an average SPEI-36 of -1.1 (moderately dry), ranging between -2.3 (extremely dry) and -0.1 (normal), while the Upper CRB experienced an average SPEI-36 of -0.96 (normal), ranging between -2.1 (extremely dry) and 1.0 (moderately wet). Post-hoc testing revealed statistically significant differences in SPEI-36 values between the PRB and the Lower CRB (p-value = 1.2×10^{-8}) and the PRB and the Upper CRB (p-value = 1.5×10^{-5}). Figure 3-3 summarizes the SPEI-18 results for each basin.

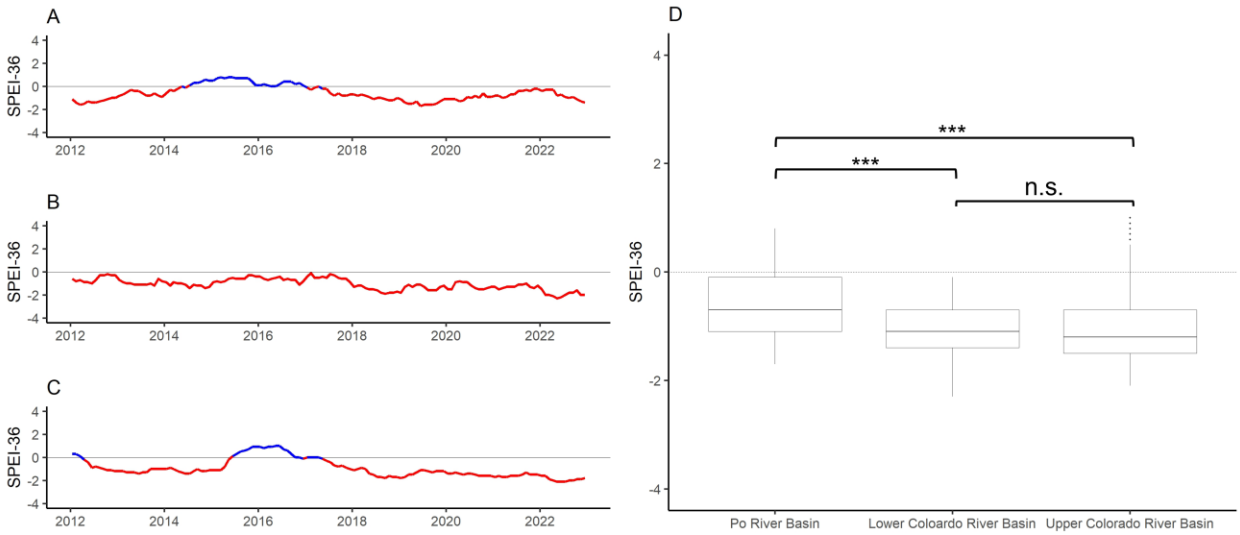

Figure 3-4; SPEI-36 from 2012 to 2022.

(A) SPEI-36 values in the PRB. (B) SPEI-36 values in the Lower CRB. (C) SPEI-36 values in the Upper CRB. (D) Comparison between SPEI-36 values across the PRB, Lower CRB, and Upper CRB.

TWSA. The PRB experienced an average TWSA value of -3.06 (drier than normal), ranging between -5.9 (drier than normal) and -0.47 (drier than normal). The Lower CRB experienced an average TWSA value of -2.19 (drier than normal), ranging between -4.98 (drier than normal) and 0.77 (near normal), while the Upper CRB experienced an average TWSA value of -1.82 (drier than normal), ranging between -5.59 (drier than normal) and 1.0 (wetter than normal). Post-hoc testing revealed statistically significant differences in TWSA values between the PRB and the Upper CRB (p-value = 0.0095). Figure 3-4 summarizes the TWSA results for each basin.

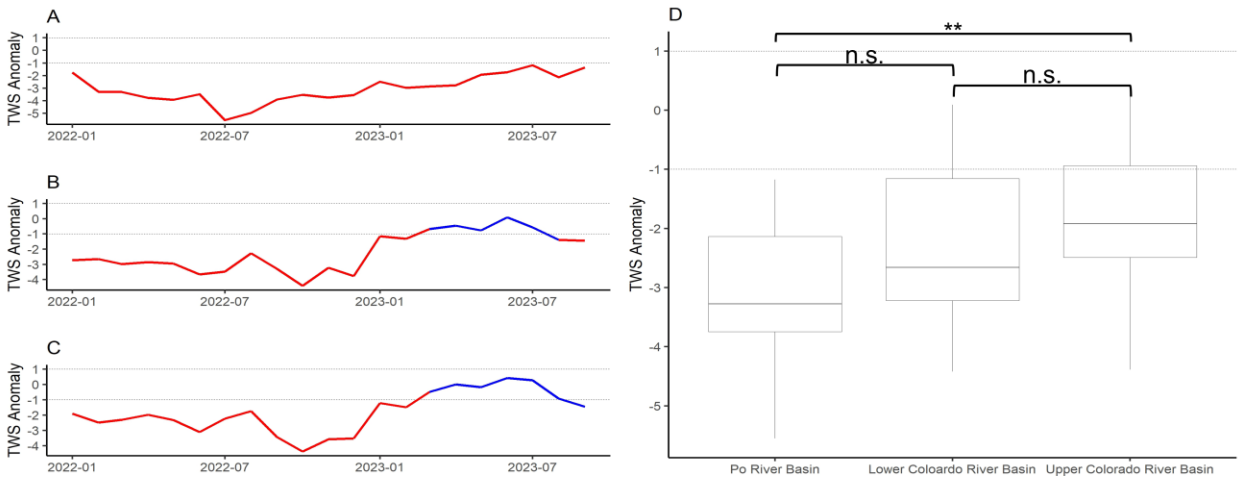

Figure 3-5; Average TWSA from January 2022 to September 2023.

(A) Average TWSA values in the PRB. (B) Average TWSA in the Lower CRB. (C) Average TWSA in the Upper CRB. (D) Comparison between Average TWSA values across the PRB, Lower CRB, and Upper CRB.

To better understand the drought conditions of the PRB and CRB, this chapter examined publicly available SPEI and TWSA data. The resulting analysis revealed the severity of drought compared to four different timescales—3 months (SPEI-3), 18 months (SPEI-18), 36 months (SPEI-36), and 20 years (TWSA)—and captured both surface and groundwater availability. In all measures, there was no significant difference in drought severity between the Upper and Lower Colorado River basins (figures 3-2 D, 3-3 D, 3-4 D, and 3-5 D). This result is contrary to expectations as the two sub-basins have varied climates, altitudes, and distinct attitudes and policies surrounding water conservation. While all regions experienced drought for a majority of the study period, the PRB averaged higher SPEI-3, SPEI-18, and SPEI-36 values—corresponding to less severe drought—than the CRB (figures 3-2 D, 3-3 D, and 3-4 D). In contrast, TWSA data reveals worse drought in the PRB compared to the CRB (figure 3-5 D). This contradiction may indicate that the SPEI is a poor predictor of groundwater availability or, perhaps more likely, drought in the PRB has had a larger impact on groundwater storage than in

the CRB. Indeed, there have been news stories emphasizing the lack of groundwater reserves in the PRB.[118] It may also be possible that consumers in the PRB are more reliant on groundwater reserves than those in the CRB. The analysis also reveals varied trends for each basin. Since the start of the study period, SPEI-36 shows drought has generally worsened for each region (figure 3-4 A-C). SPEI-18 data shows a slight improvement in drought conditions in the CRB since 2022—likely due to increased snowfall—while drought in the PRB continues to worsen (figure 3-3 A-C). However, TWSA data shows drought improvements across all regions in 2023 (figure 3-5 A-C).

Overall, the findings presented here are consistent with previous studies and news reports indicating record drought in both regions. However, there are several limitations of the chapter. The use of point data for SPEI values rather than raster formats that cover the entirety of each region removes the ability to observe within-region variations of drought. As both the PRB and CRB cover wide areas with large variations in altitude, generalizations for the whole basin may not apply to some areas. Similarly, the use of average TWSA values for each basin eliminates the observation of within-basin variation. This chapter, however, is strengthened by the use of multiple drought indices covering diverse timescales.

As shown here, the droughts of the PRB and CRB are distinct. Reduced groundwater supplies characterize drought in the PRB while higher temperatures and decreased precipitation characterize drought in the CRB. Understanding these differences is critical in assessing the most salient drought-related health consequences of each region.

[118] ANSA, “Drought,” July 26, 2022.

Chapter 4 - Salient Challenges of the Colorado and Po River Basins

Chapter 2 identified several health-related consequences of drought: air pollution, coccidioidomycosis transmission, water pollution, WNV transmission, malnutrition, migration, and poor mental health. This chapter empirically assesses the presence and severity of each health-related consequence of drought for each region. Air quality, coccidioidomycosis, water safety, and WNV are assessed directly (i.e., pollutant concentrations or case numbers) using publicly available data. To assess air quality in both regions, the author examined concentrations of $PM_{2.5}$ and PM_{10}, two critical pollutants discussed in Chapter 2. Table 4-1 shows the European Union's Air Quality Index based on pollutant concentrations. To assess water safety, the author examined groundwater nitrate and surface water phosphate as those pollutants emerged from the literature review and their concentrations are publicly available. As the consequences of malnutrition, migration, and mental health encompass a variety of illnesses, these consequences will be evaluated together through regional poverty rates.

Table 4-1; Air quality by pollutant.[119]

	Good	Fair	Moderate	Poor	Very Poor	Extremely Poor
$PM_{2.5}$ ($\mu g/m^3$)	0-10	10-20	20-25	25-50	50-75	75+
PM_{10} ($\mu g/m^3$)	0-20	20-40	40-50	50-100	100-150	150+

[119] European Environment Agency, "European Air Quality Index."

Methods: Data and Analysis

Air Quality. The author obtained Italian air quality data from the European Environment Agency (EEA) for 2013–2021.[120] The data, formatted as raster files, consisted of yearly averages of PM_{10} and $PM_{2.5}$ concentrations. U.S. air quality data was obtained from the Environmental Protection Agency (EPA) for 2013–2022.[121] The data consisted of daily PM_{10} and $PM_{2.5}$ concentrations for each environmental monitor in the U.S. To match the U.S. data to the Italian data, the author calculated, in R, the annual average pollutant concentration for each monitor in the seven CRB states. ArcGIS Pro then mapped the monitors using the latitude and longitude data from the original dataset, and the Kriging Tool performed an ordinary interpolation to rasterize the pollutant concentration data across the CRB.[122] Once the air quality data for each basin shared formats, the author used the Extract by Mask tool in ArcGIS Pro to select cells within each basin. ArcGIS Pro then calculated zonal statistics (mean, minimum, and maximum concentration) for each province or county. The author then calculated descriptive statistics and Pearson's correlation in RStudio. Average pollutant concentrations for each province or county were visualized in ArcGIS Pro, and figures for descriptive and inferential statistics were visualized using the ggplot2 package in RStudio.

Coccidioidomycosis. County-level Valley Fever data is only available in Arizona and California. The author obtained California Valley Fever data from the California Department of Public Health's online dashboard and Arizona data from the Arizona Department of Health

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[120] European Environment Agency, "Nitrate in Groundwater (2000-2021)"; European Environment Agency, "Phosphate in Rivers (2000-2021)."

[121] Enivronmnetal Protection Agency, "AirData File Download Page."

[122] The EEA used similar methods to interpolate European air quality data, albeit with additional considerations to other factors (e.g., altitude).

Services' annual reports.[123] State-level Valley Fever data for Nevada, New Mexico, Utah, and Wyoming was obtained from the CDC.[124] Coccidioidomycosis is not reportable in Colorado and no county or state-level data is available. State-level data was then joined with US Census population estimates to calculate annual incidence per 100,000[125]. Once county-level data from Arizona and California were joined with state-level data from Nevada, New Mexico, Utah, and Wyoming, the author calculated total cases and average, median, minimum, and maximum incidence for each area. Valley Fever data were then joined with CRB SPEI data, and R was used to generate descriptive statistics, Pearson's correlation, and figures.

Water Safety. To examine water safety in each basin, the author obtained groundwater nitrate and surface water phosphorus data from the EEA and the U.S. Water Quality Portal.[126] European nitrate and phosphorus data consisted of annual (2013–2021) average concentrations for each monitor. The author only downloaded European data for the approximate area of northern Italy and then used ArcGIS Pro to extract monitors in the PRB. U.S. data consisted of individual monitor readings for a variety of pollutants across the seven CRB states. As geographic information for each monitor was unavailable, the author was unable to restrict the analysis to monitors within the CRB. The author only considered rows containing nitrate (subsurface water) or phosphorus (surface water) measurements. The author then calculated the annual average

[123] California Department of Public Health, "Valley Fever in California Dashboard"; Arizona Department of Health Services, "AZDHS | Epidemiology & Disease Control - Valley Fever."

[124] Centers for Disease Control and Prevention, "Weekly Statistics from the National Notifiable Diseases Surveillance System (NNDSS)."

[125] US Census Bureau, "County Population Totals"; US Census Bureau, "County Population Totals and Components of Change."

[126] European Environment Agency and European Environment Agency, "WISE Statistics - Nutrients (1990-2021), 2023"; Washington (DC): National Water Quality Monitoring Council, United States Geological Survey (USGS), and Environmental Protection Agency (EPA), "Water Quality Portal."

nitrate and phosphorus readings for each monitor. Descriptive statistics, Pearson's correlation with SPEI data, and figures were generated in R.

WNV. The author obtained Italian WNV data from the European Center for Disease Control (ECDC) for 2013–2022.[127] Data consisted of yearly total WNV cases reported and the total population in each province. U.S. WNV data was obtained from the U.S. Centers for Disease Control and Prevention (CDC) for 2013–2022.[128] Data consisted of yearly non-neuroinvasive, neuroinvasive, and asymptomatic WNV cases for each county. Yearly population estimates for each county were obtained from the U.S. Census.[129] The author then calculated the total WNV cases by adding all case types. Once datasets were cleaned and formatted in RStudio and ArcGIS Pro, yearly incidence (expressed as incidence per 100,000 residents) was then calculated for each county and province by dividing the total WNV cases by the total population. Cumulative incidence was then calculated by dividing the total cases by the average population over the study period. The author then mapped yearly and cumulative incidence using ArcGIS Pro. Descriptive statistics were calculated in RStudio. The author used the Pearson correlation test to assess the association between cases and SPEI-3, SPEI-18, and SPEI-36.

Poverty. To assess the risk of malnutrition, migration, and mental health, the author obtained relative poverty data from the Italian National Institute of Statistics and the US Census.[130] Italian poverty data consisted of relative poverty incidence per household for each region, and US data

[127] European Centre for Disease Prevention and Control, "Weekly Updates."

[128] CDC, "Historic Data (1999-2022) | West Nile Virus | CDC."

[129] US Census Bureau, "County Population Totals"; US Census Bureau, "County Population Totals and Components of Change."

[130] Italian National Institute of Statistics, "Poor Households - Region Residence"; US Census Bureau, "SAIPE Datasets."

consisted of the percentage of the population in poverty for each county. R was used to generate descriptive statistics, Pearson's correlation, and figures.

Results and Discussion

Air Quality. From 2013–2021, the PRB experienced an average PM_{10} concentration of 19.72 $\mu g/m^3$ (good) and an average $PM_{2.5}$ concentration of 13.81 $\mu g/m^3$ (fair). Average PM_{10} concentrations ranged from 0 $\mu g/m^3$ (good) to 47.3 $\mu g/m^3$ (moderate) with an average minimum value of 7.5 $\mu g/m^3$ (good) and an average maximum value of 33.7 $\mu g/m^3$ (fair). Average $PM_{2.5}$ concentrations ranged from 0 $\mu g/m^3$ (good) to 35.6 $\mu g/m^3$ (poor) with an average minimum value of 4.4 $\mu g/m^3$ (good) and an average maximum value of 24.6 $\mu g/m^3$ (moderate). Figure 4-1 shows the average pollutant concentrations in the PRB for the study period. Neither average PM_{10} nor $PM_{2.5}$ had a statistically significant correlation with SPEI (figures 4-3 and 4-4).

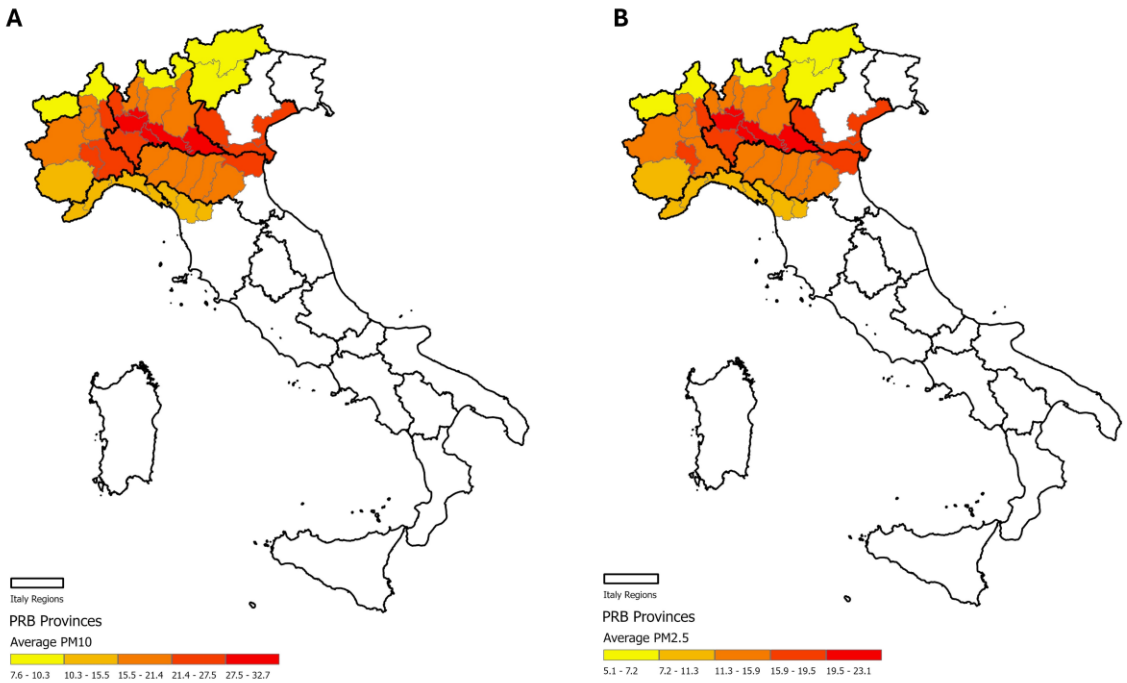

Figure 4-1; Average PM_{10} (A) and $PM_{2.5}$ (B) concentrations in the PRB from 2013–2021.

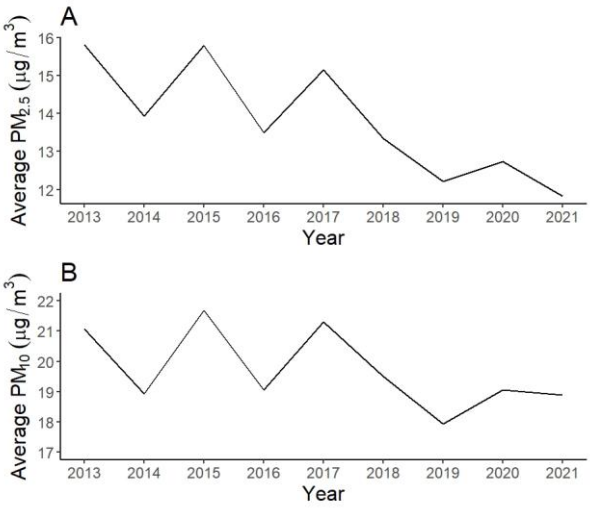

Figure 4-2; Annual average $PM_{2.5}$ (A) and PM_{10} (B) concentrations in the PRB.

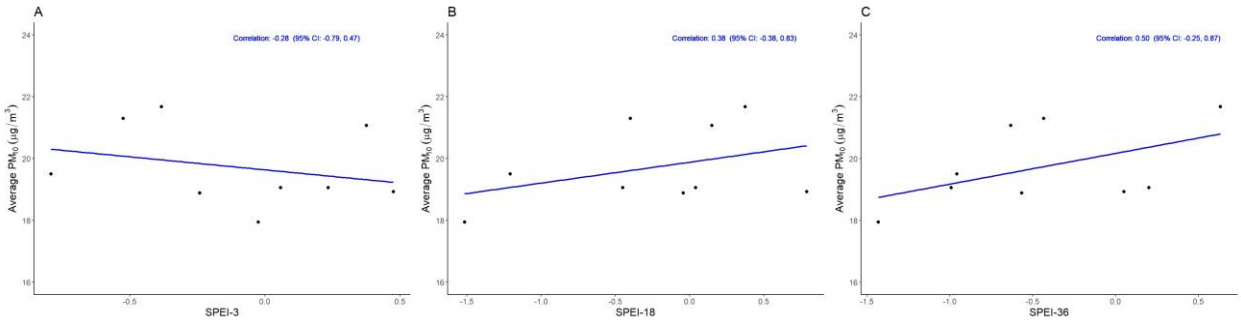

Figure 4-3; Correlations between annual average PM_{10} concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the PRB.

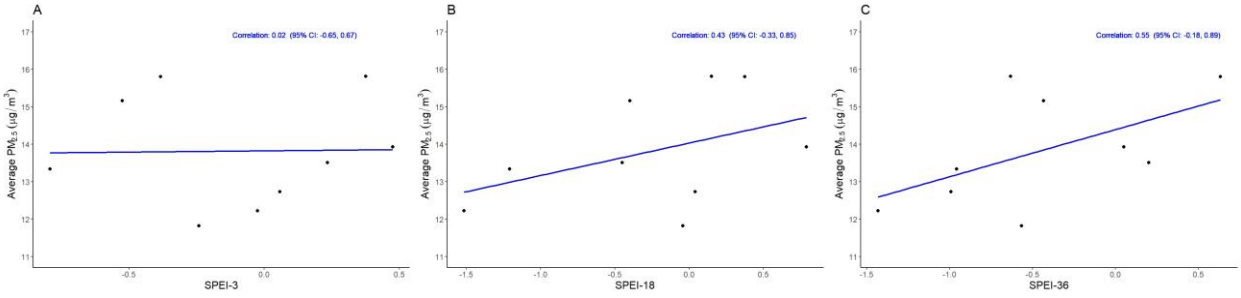

Figure 4-4; Correlations between annual average $PM_{2.5}$ concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the PRB.

From 2013–2022, the CRB experienced an average PM_{10} concentration of 19.33 $\mu g/m^3$ (good) and an average $PM_{2.5}$ concentration of 6.4 $\mu g/m^3$ (good) (figure 4-6). Average PM_{10} concentrations ranged from 6.4 $\mu g/m^3$ (good) to 120.3 $\mu g/m^3$ (very poor) with an average minimum value of 12.3 $\mu g/m^3$ (good) and an average maximum value of 29.6 $\mu g/m^3$ (fair). Average $PM_{2.5}$ concentrations ranged from 0.9 $\mu g/m^3$ (good) to 30.5 $\mu g/m^3$ (poor) with an average minimum value of 4.3 $\mu g/m^3$ (good) and an average maximum value of 8.7 $\mu g/m^3$ (good). Figure 4-5 shows the average pollutant concentrations in the CRB for the study period. There were statistically significant correlations between PM_{10} and SPEI-3 (r^2 = -0.75, 95% CI: -0.94, -0.24) and SPEI-18 (r^2 = -0.64, 95% CI: -0.90, -0.01) but not SPEI-36 (figure 4-7). There were no statistically significant correlations between PM2.5 and SPEI (figure 4-8).

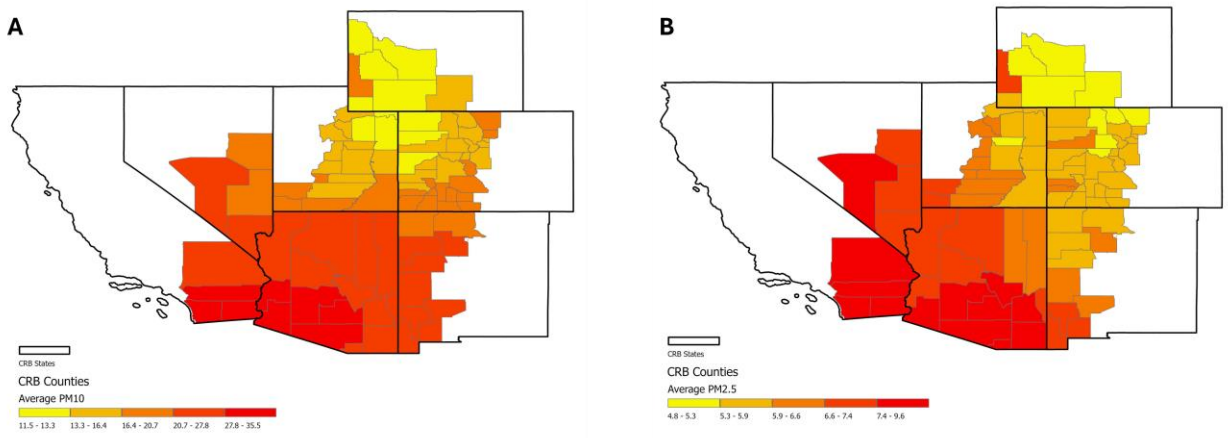

Figure 4-5; Average PM_{10} (A) and $PM_{2.5}$ (B) concentrations in the CRB from 2013–2022.

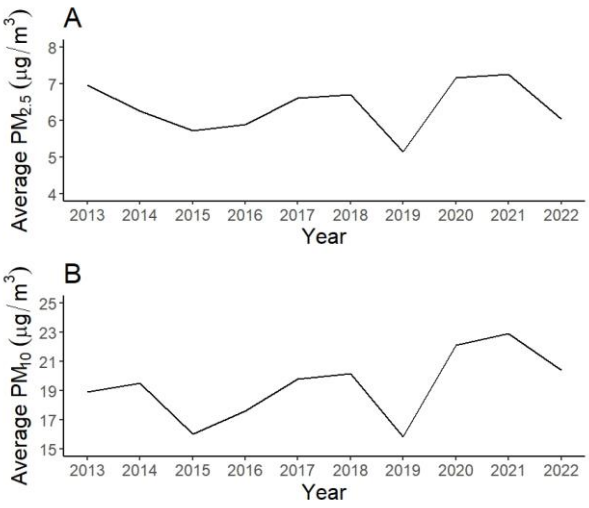

Figure 4-6; Annual average $PM_{2.5}$ (A) and PM_{10} (B) concentrations in the CRB.

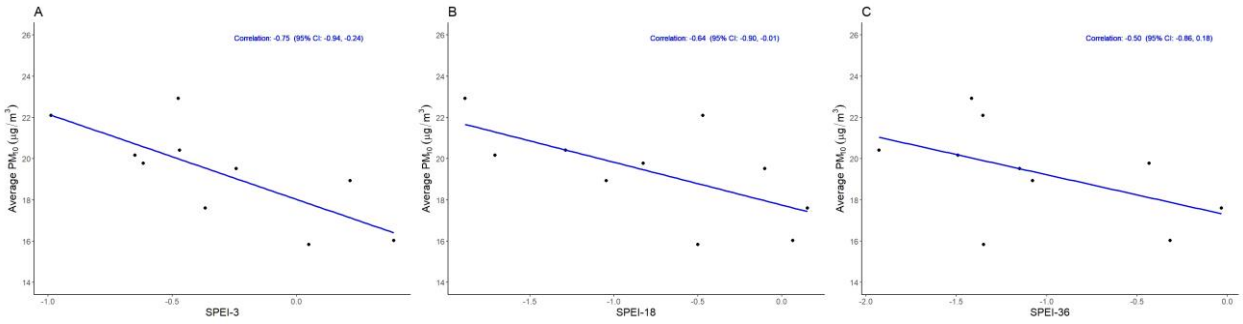

Figure 4-7; Correlations between annual average PM_{10} concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the CRB.

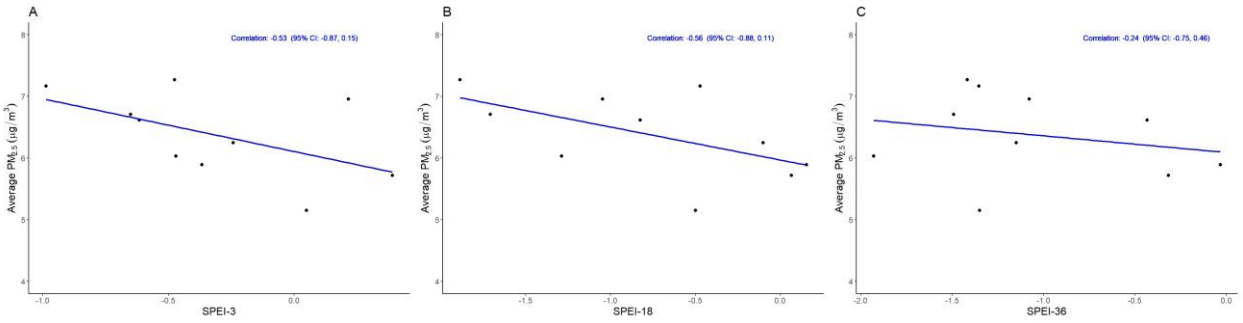

Figure 4-8; Correlations between annual average $PM_{2.5}$ concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the CRB.

Coccidioidomycosis. The CRB reported 90,861 cases of coccidioidomycosis with an average annual incidence of 43.47 cases per 100,000 residents. Pinal County, Arizona, reported the highest average incidence of 162.5 cases per 100,000 (figure 4-9). Valley Fever cases peaked in the CRB in 2021 with 12,901 cases and an incidence of 59.9 cases per 100,000 (figure 4-10). Annual Valley Fever case incidences ranged from 0 cases to 258.3 cases per 100,000, with an average minimum incidence of 26.8 cases per 100,000 and an average maximum incidence of 68.2 cases per 100,000. Figure 4-9 shows the average incidence of Valley Fever in the CRB during the study period. There were no statistically significant correlations between median valley fever incidence and SPEI (figure 4-11).

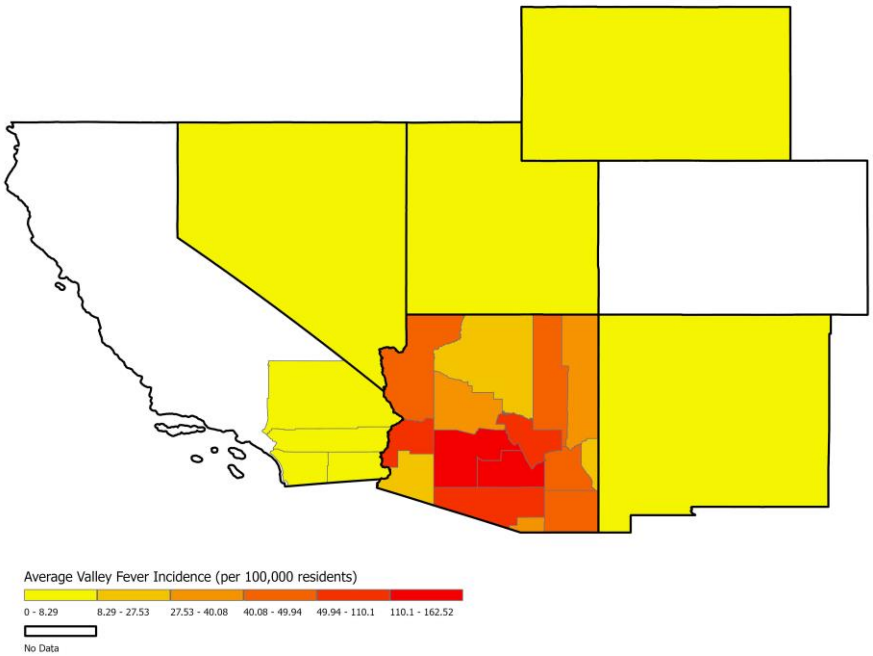

Figure 4-9; Average Valley Fever incidence per 100,000 residents in the CRB from 2013-2022.

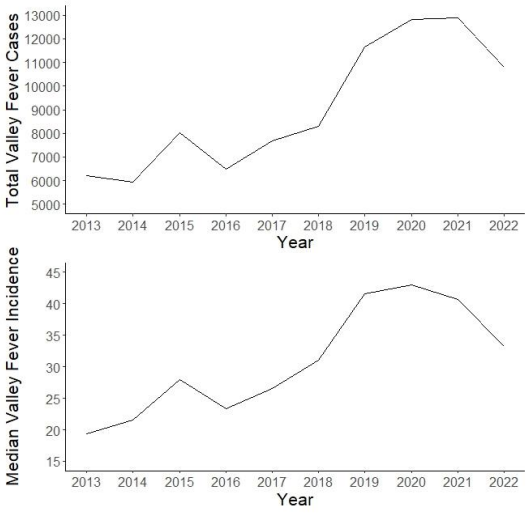

Figure 4-10; Annual Valley Fever cases and median incidence in the CRB.

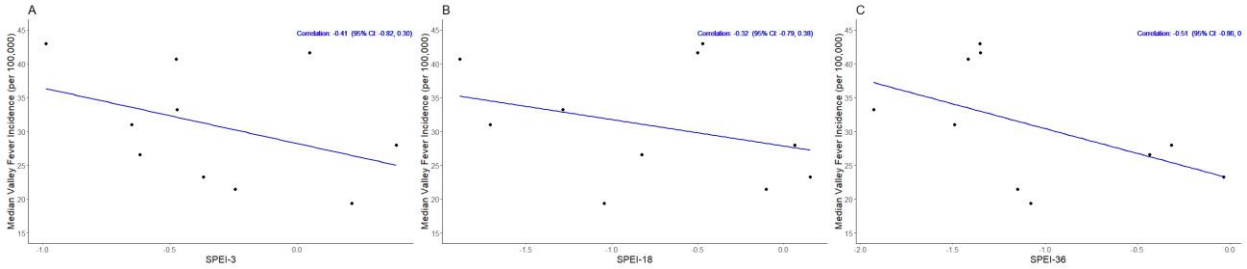

Figure 4-11; Correlation between median Valley Fever incidence and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C).

Water Safety. From 2013–2021, PRB groundwater nitrate and surface water phosphorus concentrations averaged 24.2 and 0.086 mg/L, respectively (figure 4-12). Nitrate concentrations ranged from 0.92 to 435.9 mg/L with an average minimum value of 14.9 mg/L and an average maximum value of 55.8 mg/L. Phosphorus concentrations ranged from 0.00001 to 3.83 with an average minimum value of 0.05 mg/L and an average maximum value of 0.14 mg/L. Nitrate concentrations peaked in 2020, with an average concentration of 53.5 mg/L (figure 4-12). Conversely, phosphorus concentrations peaked in 2013, with an average concentration of 0.13 mg/L (figure 4-12). There were no statistically significant correlations between annual average

nitrate concentrations and SPEI values; however, there were significant associations between annual average phosphorus concentrations and SPEI-3 (r^2 = 0.75, 95% CI: 0.16, 0.94) and SPEI-18 (r^2 = 0.69, 95% CI: 0.05, 0.93) (figures 4-13 and 4-14).

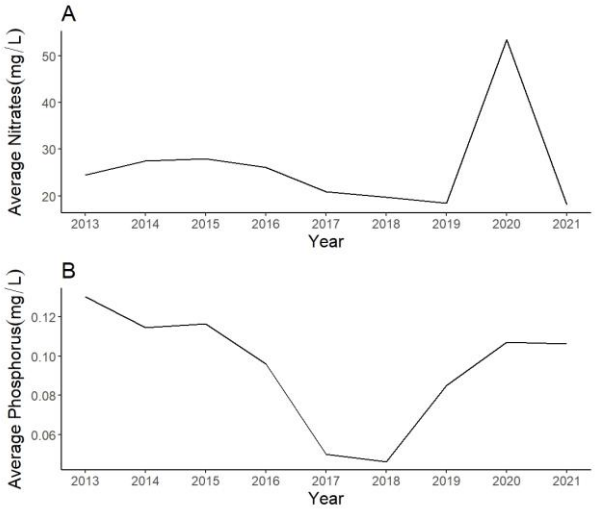

Figure 4-12; Annual average nitrate (A) and phosphorus (B) concentrations in the PRB.

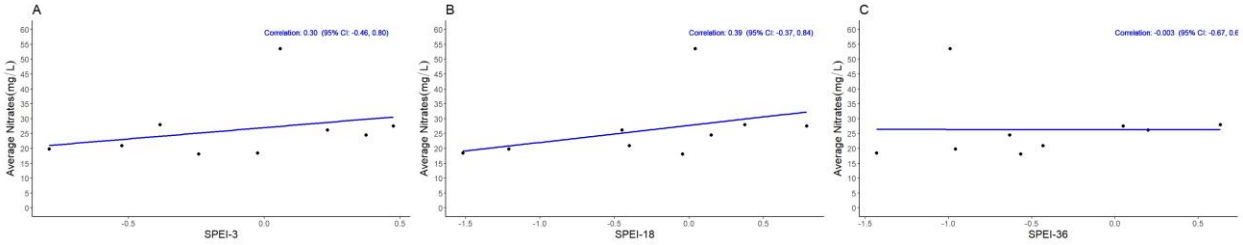

Figure 4-13; Correlations between average annual nitrate concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the PRB.

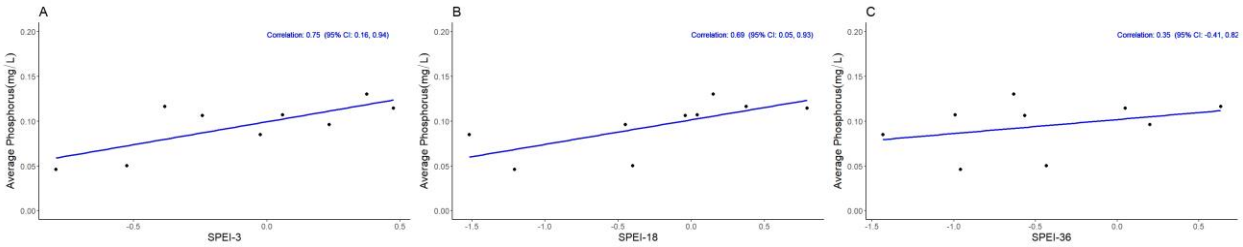

Figure 4-14; Correlations between average annual phosphorus concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the PRB.

In the seven CRB states, groundwater nitrate and surface water phosphorus concentrations averaged 88.2 and 18.7 mg/L, respectively (figure 4-15). Nitrate concentrations ranged from 0.2 to 1845.5 mg/L with an average minimum concentration of 85.6 mg/L and an average maximum concentration of 91.3 mg/L. Phosphorus concentrations ranged from 0 to 27,900 mg/L with an average minimum concentration of 13.2 mg/L and an average maximum concentration of 25.5 mg/L. Nitrate concentrations peaked in 2018, with an average concentration of 311.5 mg/L, while phosphorus concentrations peaked in 2015, with an average concentration of 26.7 mg/L. There were no statistically significant correlations between annual average nitrate concentrations and SPEI values; however, there were significant associations between annual average phosphorus concentrations and SPEI-3 (r^2 = 0.68, 95% CI: 0.08, 0.92) and SPEI-36 (r^2 = 0.71, 95% CI: 0.14, 0.93) (figures 4-16 and 4-17).

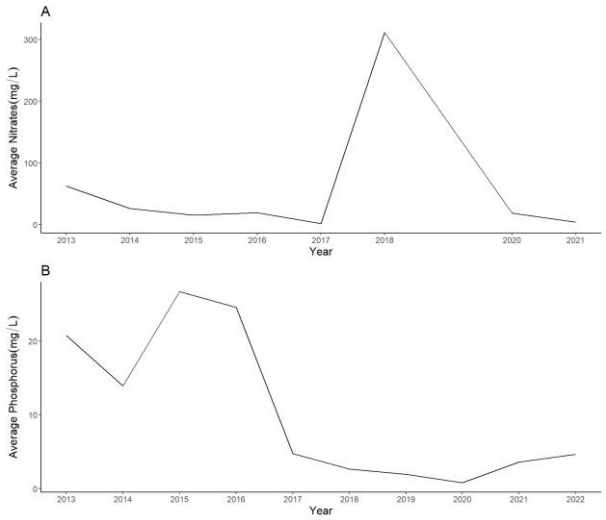

Figure 4-15; Annual average nitrate (A) and phosphorus (B) concentrations in the CRB.

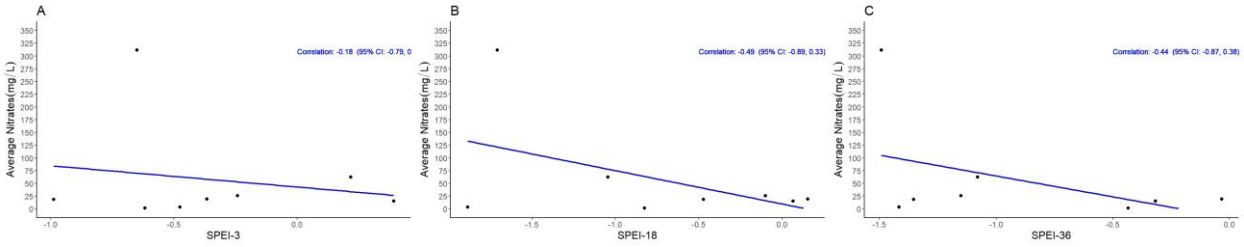

Figure 4-16; Correlations between average annual nitrate concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the CRB.

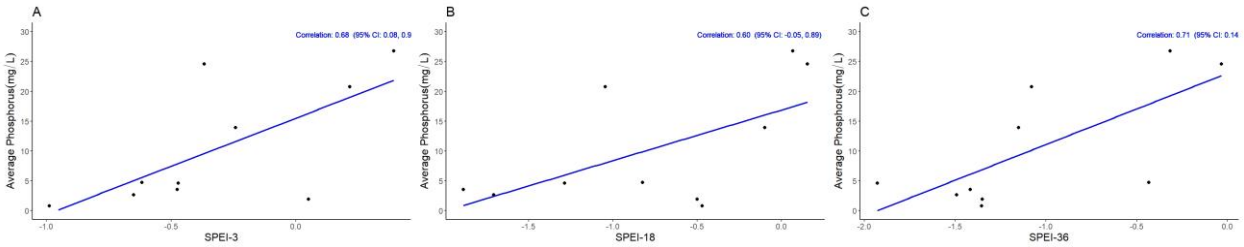

Figure 4-17; Correlations between average annual phosphorus concentrations and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the CRB.

West Nile Virus. From 2013–2022, the PRB reported 1,182 cases of WNV for an average cumulative incidence of 8.3 cases per 100,000 residents, with Rovigo Province having the highest cumulative incidence of 40.5 cases per 100,000 residents (figure 4-18). WNV cases peaked in 2018 and 2022 as the PRB reported 403 and 389 cases, respectively, corresponding to an average incidence of 3.1 cases per 100,000 in 2018 and 2022 (figure 4-19). Figure 4-18 shows WNV incidence across all PRB provinces for each year. Pearson's correlation test found statistically significant negative associations between annual WNV cases and SPEI-3 (r^2 = -0.75, 95% CI: -0.94, -0.23) as well as the annual number of provinces reporting and SPEI-3 (r^2 = -0.68, 95% CI: -0.92, -0.09) (figure 4-20). Associations with SPEI-18 and SPEI-36 also trended negative but are not statistically significant (figure 4-20).

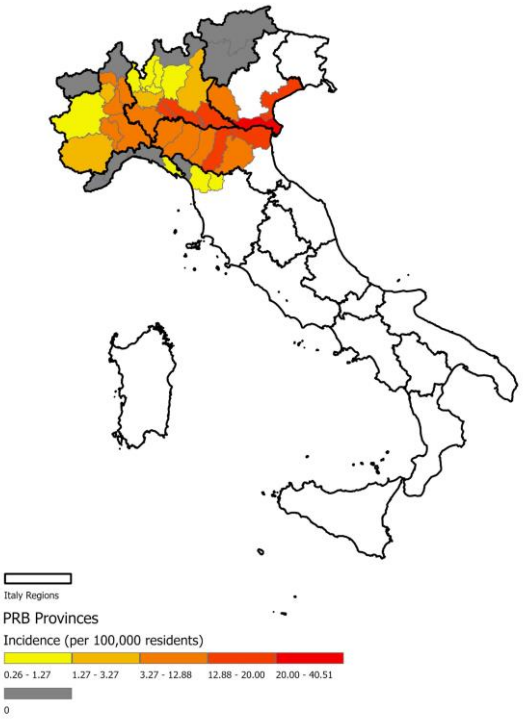

Figure 4-18; Average annual WNV incidence in the PRB.

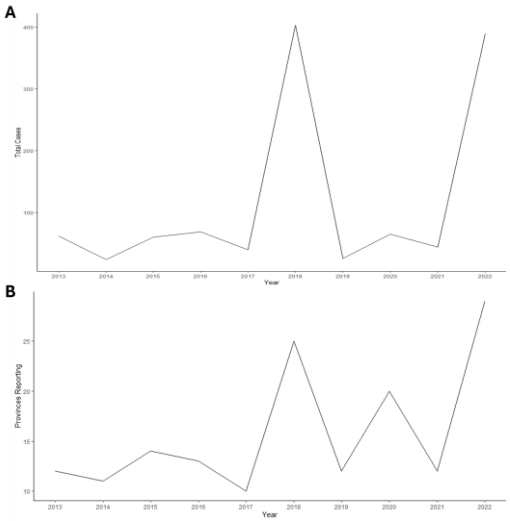

Figure 4-19; Annual average WNV cases (A) and number of provinces reporting (B) in the PRB.

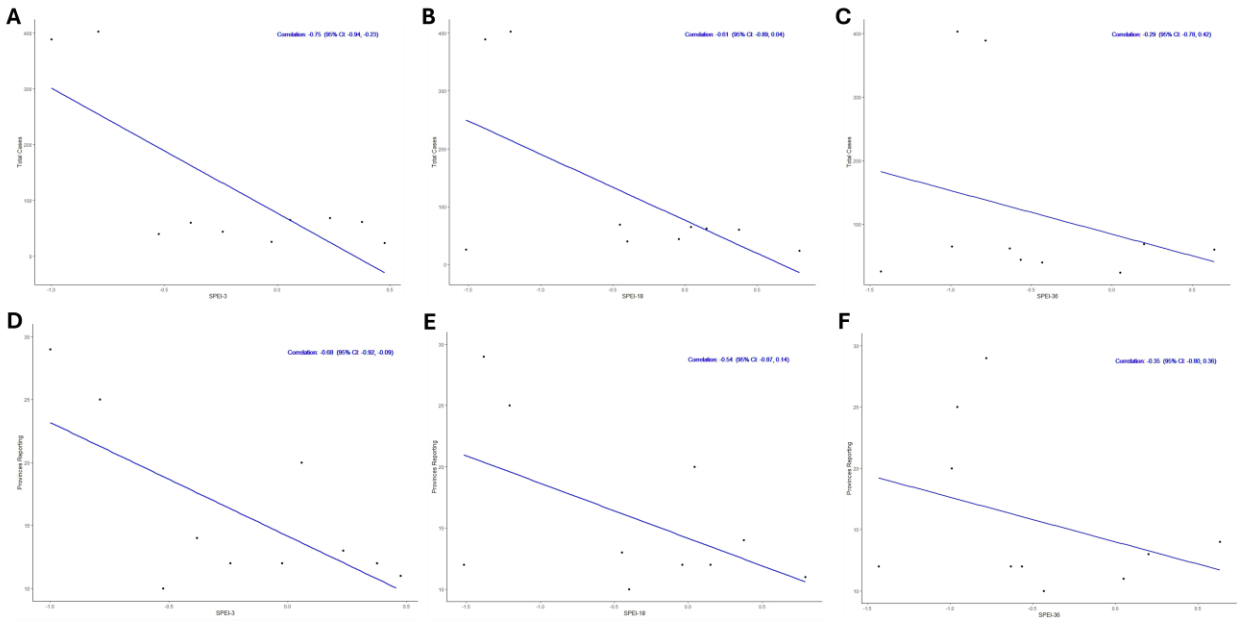

Figure 4-20; Correlations between average annual WNV cases and number of provinces reporting and SPEI in the PRB.

From 2013–2022, the Lower CRB reported 7,234 WNV cases for an average cumulative incidence of 11.2 cases per 100,000 residents, with Maricopa County, Arizona, having the highest cumulative incidence of 52 cases per 100,000 residents (figure 4-21). In the same period, the Upper CRB reported 1,920 cases for an average cumulative incidence of 26.8 cases per 100,000 residents, with Delta County, Colorado, having the highest cumulative incidence of 368 cases per 100,000 residents (figure 4-21). WNV cases peaked in the Lower CRB in 2021 as it reported 1,986 cases, corresponding to an average incidence of 5.4 cases per 100,000 (figure 4-22). WNV cases peaked in the Upper CRB in 2013 as it reported 442 cases, corresponding to an average incidence of 9.9 cases per 100,000 (figure 4-22). Figure 4-21 shows WNV incidence across all CRB counties for each year. For the Lower CRB, Pearson's correlation test found statistically significant positive associations between annual WNV cases and SPEI-36 ($r^2 = 0.64$, 95% CI: 0.02, 0.91) as well as annual number of counties reporting and SPEI-36 ($r^2 = 0.64$, 95% CI: 0.02, 0.91) (figure 4-23). Associations with SPEI-3 also trended positively but were not statistically significant. The association between the number of counties reporting and SPEI-18 trended negative while the association between annual WNV cases and SPEI-18 trended positive (figure 4-23). For the Upper CRB, Pearson's correlation test found a statistically significant positive association between annual number of counties reporting and SPEI-3 ($r^2 = 0.71$, 95% CI: 0.14, 0.93) (figure 4-24). No other associations were significant (figure 4-24).

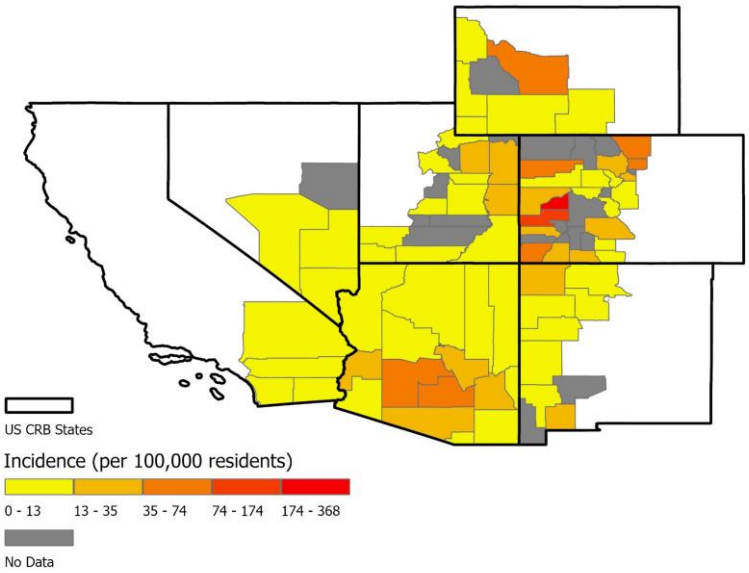

Figure 4-21; Average annual WNV incidence in the CRB.

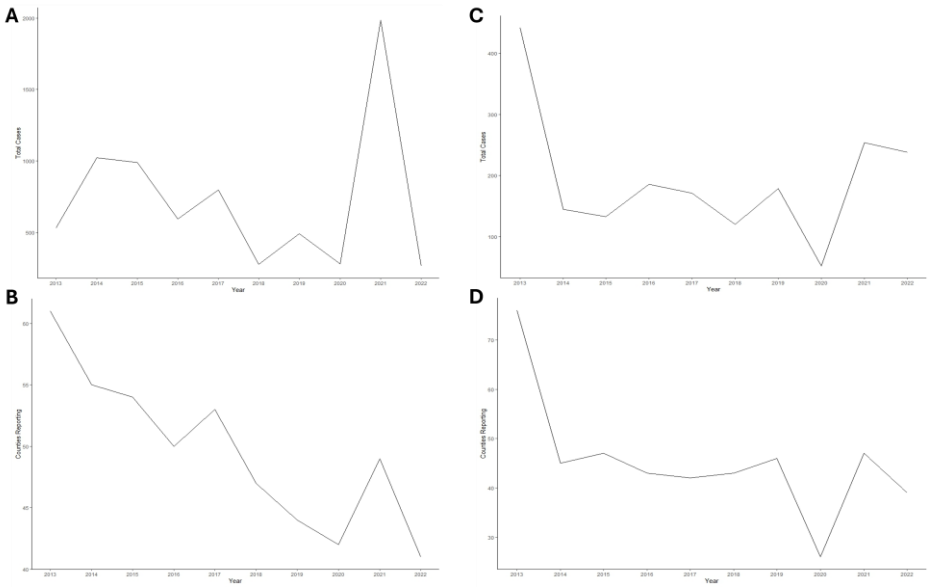

Figure 4-22; Annual WNV cases in the Lower (A) and the Upper CRB (C) and number of counties reporting in the Lower (B) and Upper (D) CRB.

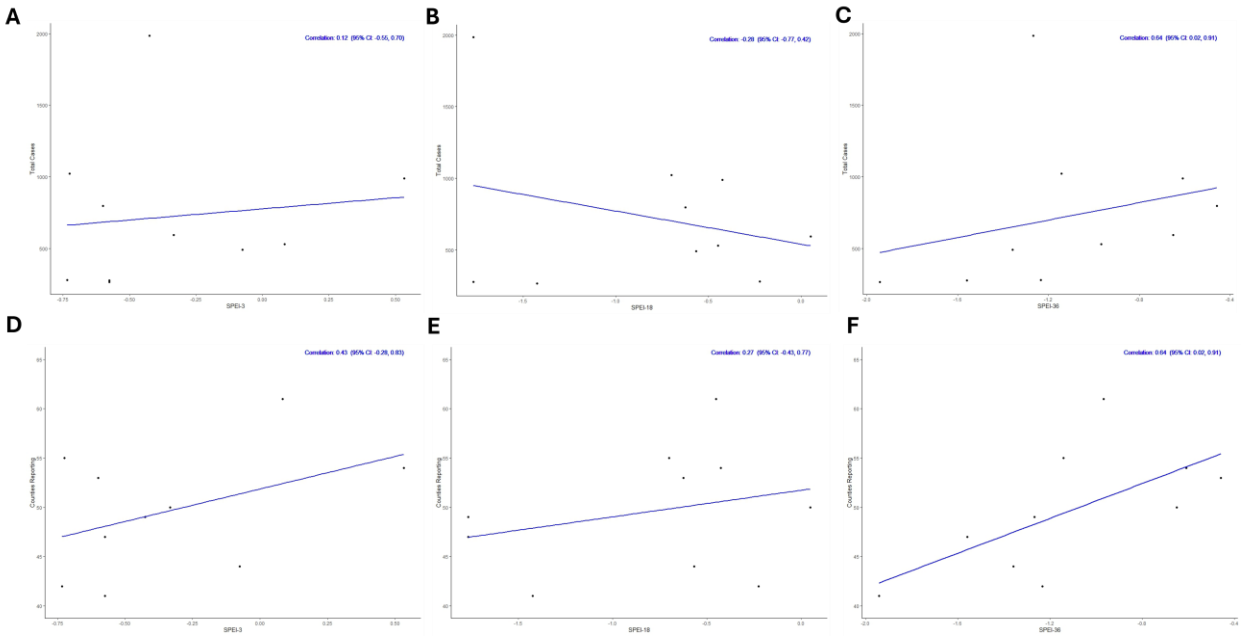

Figure 4-23; Correlations between total WNV cases and number of counties reporting and SPEI in the Lower CRB.

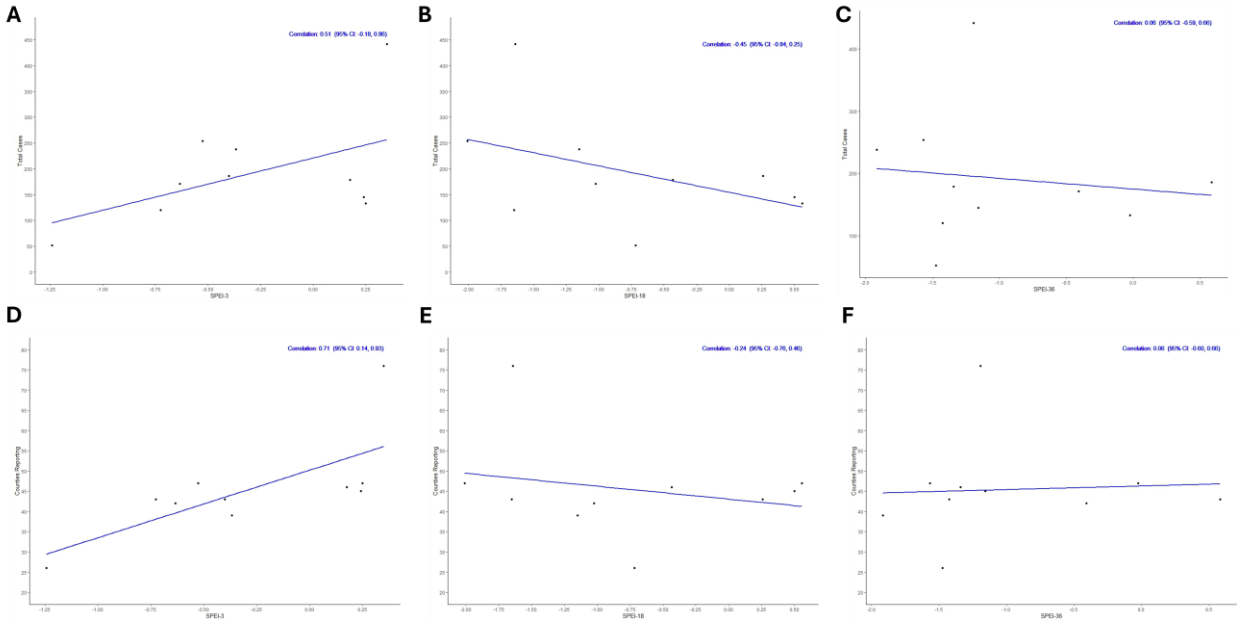

Figure 4-24; Correlations between total WNV cases and number of counties reporting and SPEI in the Upper CRB.

Poverty. The PRB experienced an average relative poverty incidence of 5.6% (of households) from 2014–2022 (figure 4-25). The poverty incidence ranged from 3.2% to 11.7% with an average minimum incidence of 4.3% and an average maximum incidence of 7.6%. Poverty incidence peaked in 2016 with an average incidence of 6.4% (figure 4-26). There were no statistically significant correlations between poverty incidence and SPEI (figure 4-27).

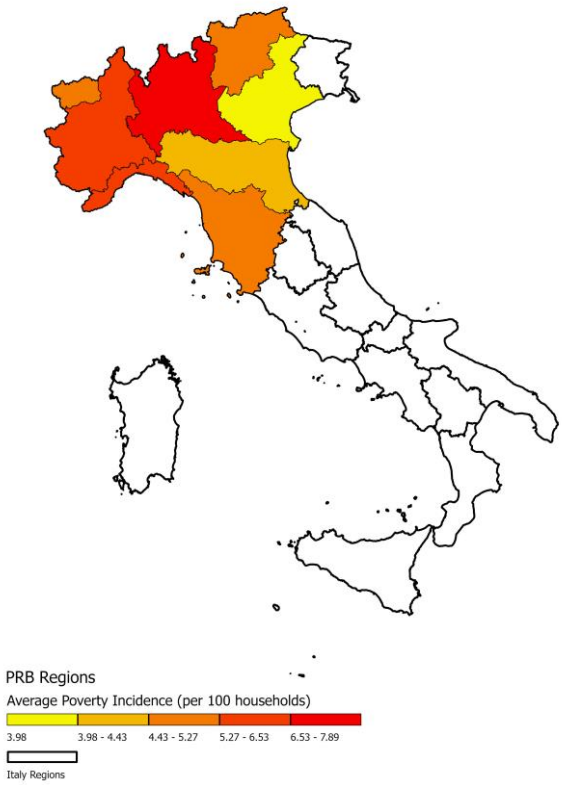

Figure 4-25; Average annual poverty incidence in the PRB.

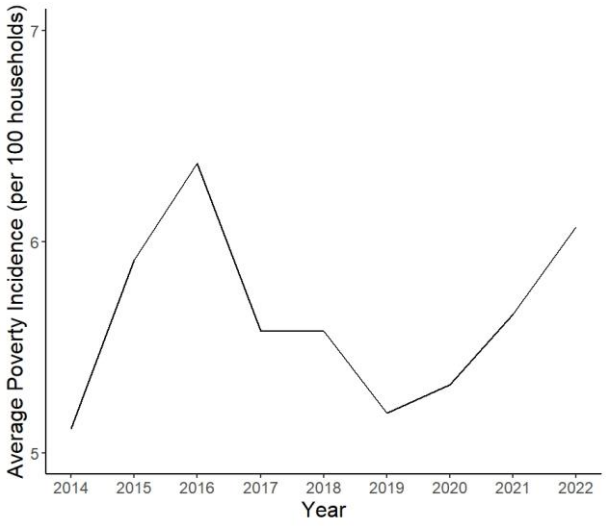

Figure 4-26; Annual average poverty incidence in the PRB.

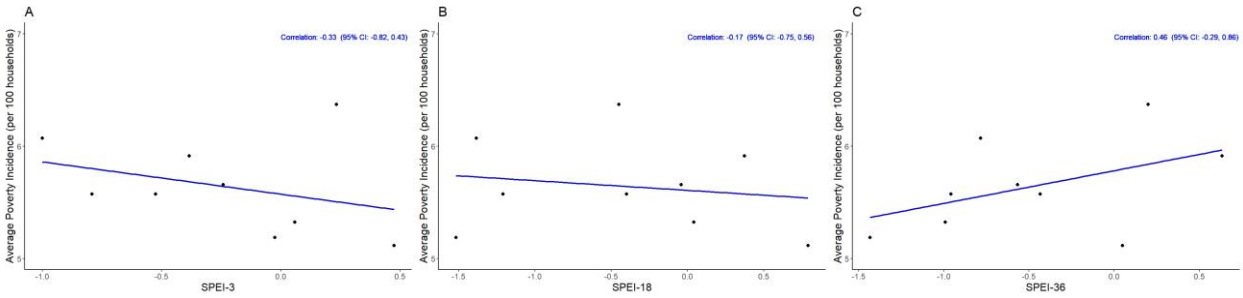

Figure 4-27; Correlations between average annual poverty incidence and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the PRB.

The CRB experienced an average poverty rate of 14.42% (of individuals) from 2013–2022 (figure 4-29). The poverty rate ranged from 3.6% to 38.7% with an average minimum rate of 10.73% and an average maximum rate of 19.4% (figure 4-28). Poverty rates peaked in 2014 with an average rate of 15.9% (figure 4-29). There was a statistically significant correlation between the average poverty rate and SPEI-3 (r^2 = 0.63, 95% CI: 0.003, 0.90), but there were no significant associations with SPEI-18 or SPEI-36 (figure 4-30).

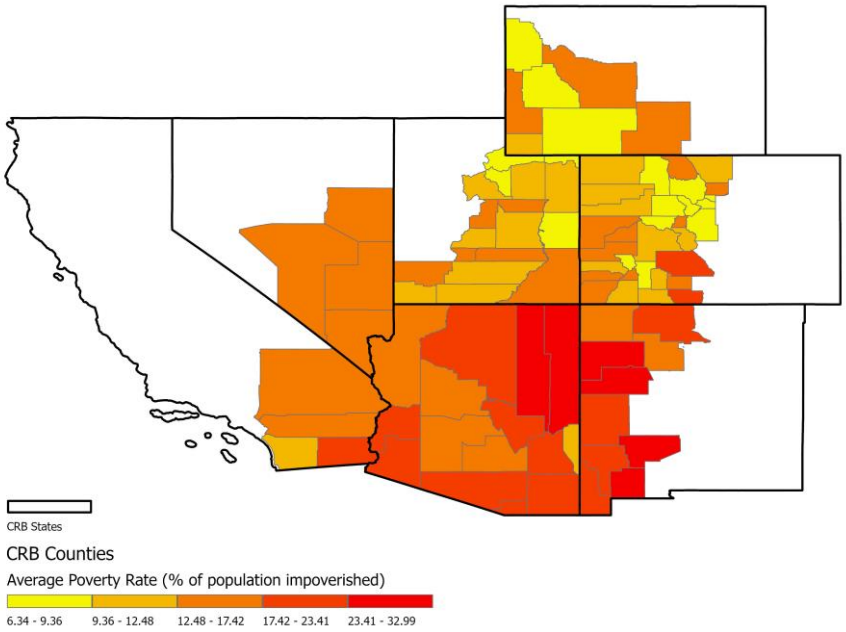

Figure 4-28; Average annual poverty rates in the CRB.

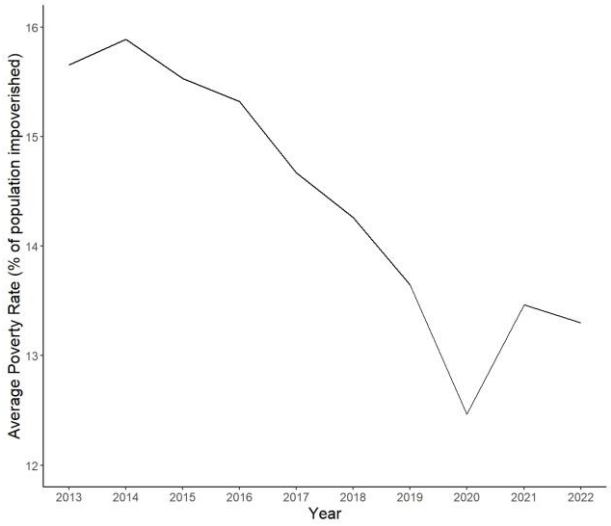

Figure 4-29; Annual average poverty rate in the CRB.

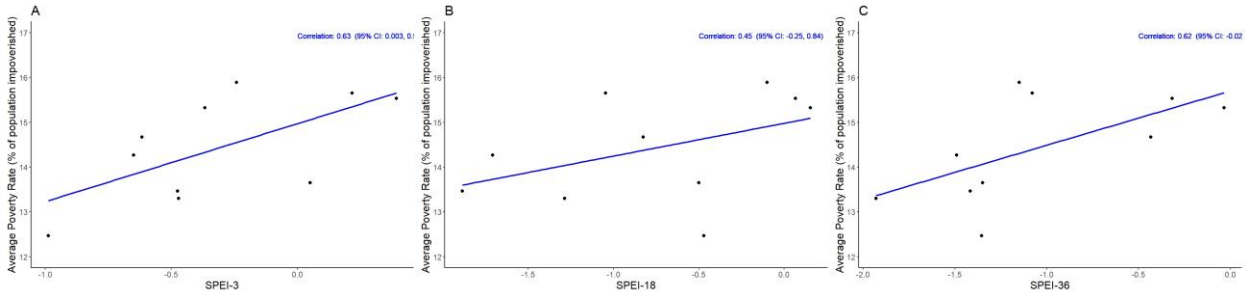

Figure 4-30; Correlations between average annual poverty rates and SPEI-3 (A), SPEI-18 (B), and SPEI-36 (C) in the CRB.

This chapter used publicly available data to assess the presence and severity of the health-related consequences of drought identified in Chapter 2. The author used PM_{10} and $PM_{2.5}$ data to assess air quality in the PRB and CRB. In the PRB, PM_{10} concentrations averaged 19.77 $\mu g/m^3$ with an average range of 7.5–33.7 $\mu g/m^3$, and in the CRB, PM_{10} concentrations averaged 19.33 $\mu g/m^3$ with an average range of 12.3–29.6 $\mu g/m^3$. The average PM_{10} concentrations for both

regions correspond to an air quality index of "good," and the average maximum concentrations for each region correspond to an AQI of "fair." However, the PRB's and CRB's average PM_{10} concentration exceeds the World Health Organization's (WHO) recommendation of 15.6 μg/m-3.[131] The PRB's maximum PM_{10} concentration was 47.3 $\mu g/m^3$, corresponding to an AQI of "moderate," and the CRB's was 120.3 $\mu g/m^3$, corresponding to an AQI of "very poor." Thus, while the typical PM_{10} concentrations for each basin are similarly low, the CRB experienced more severe anomalies than the PRB. This finding may be explained by the occurrence of large dust storms (called haboobs) in the CRB's desert areas that dramatically decrease air quality. In the PRB, $PM_{2.5}$ concentrations averaged 13.81 $\mu g/m^3$ with an average range of 4.4–24.6 $\mu g/m^3$, and in the CRB, $PM_{2.5}$ concentrations averaged 6.4 $\mu g/m^3$ with an average range of 4.3–8.7 $\mu g/m^3$. The average $PM_{2.5}$ concentration for the PRB corresponds to an AQI of "fair," while that of the CRB corresponds to an AQI of "good." As with PM_{10}, the average $PM_{2.5}$ concentration of each basin exceeded the 5 $\mu g/m^3$ recommended by the WHO.[132] The average maximum concentration in the PRB corresponds to a "moderate" AQI, and the average maximum of the CRB corresponds to an AQI of "good." The maximum $PM_{2.5}$ concentrations of the PRB and the CRB—35.6 and 30.5 $\mu g/m^3$, respectively—both correspond to an AQI of "poor." Despite the CRB having equally severe anomalies, $PM_{2.5}$ concentrations are generally higher in the PRB. This result matches expectations as the PRB's geography—with the Alps to the North and West and the Apennines to the South—traps air pollution (primarily generated by industrial manufacturing) in the Po River Valley. Considering PM_{10} and $PM_{2.5}$ together, the PRB typically experiences worse air quality than the CRB.

[131] WHO, "What Are the WHO Air Quality Guidelines?"

[132] WHO.

To assess the severity of coccidioidomycosis in the CRB, the author examined county-level data from Arizona and California as well as state-level data from Nevada, New Mexico, Utah, and Wyoming. Across the seven CRB states, excluding Colorado and non-CRB California counties, the average incidence of Valley Fever was 43.47 cases per 100,000 residents, ranging from an average minimum incidence of 26.8 cases per 100,000 residents to an average maximum incidence of 68.2 cases per 100,000 residents. As coccidioidomycosis is only endemic to the Americas, Valley Fever cases represent an increased public health burden of drought on the CRB.

This chapter used groundwater nitrate and surface water phosphorus data to assess water safety in the PRB and CRB. In the PRB, groundwater nitrate concentrations averaged 24.2 mg/L with an average range of 14.9–55.8 mg/L, and in the CRB, nitrate concentrations averaged 88.2 mg/L with an average range of 85.6–91.3 mg/L. The maximum nitrate concentration was 435.9 mg/L in the PRB and 1845.5 mg/L in the CRB. Thus, groundwater nitrate concentrations are higher in the CRB than in the PRB. Similar differences between the PRB and CRB exist for phosphorus contamination. In the PRB, surface water phosphorus concentrations averaged 0.086 mg/L with an average range of 0.05–0.14 mg/L, and in the CRB, concentrations averaged 18.7 mg/L with an average range of 13.2–25.5 mg/L. The maximum phosphorus concentration was 3.83 mg/L in the PRB and 27,900 mg/L in the CRB. As with nitrates, the CRB experienced higher phosphorus contamination than the PRB. These findings are consistent with existing regulatory structures in both basins. The European Union (EU) regulates nitrate concentrations in both natural and treated water in addition to regulating agricultural fertilizer use. [133] In contrast,

[133] European Union, Directive (EU) 2020/2184 of the European Parliament and of the Council on the quality of water intended for human consumption (recast); Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources.

the U.S. only regulates nitrate concentrations in treated potable water and lacks robust regulations for fertilizer use.[134] Phosphorus concentrations, however, remain unregulated in both the E.U. and the U.S. Considering both nitrate and phosphorus concentrations, the CRB experiences increased water safety risk compared to the PRB.

Using case and incidence data, this chapter assessed WNV severity in both the PRB and CRB. The PRB experienced a cumulative WNV incidence of 8.3 cases per 100,00 residents, while the Lower CRB experienced an incidence of 11.2 cases per 100,000 and the Upper CRB an incidence of 26.8 cases per 100,000. Thus, the CRB experienced higher rates of WNV than the PRB. This finding is contrary to expectations as WNV was first detected in the PRB in 1998, a year before the first cases were reported in New York. Additionally, the lack of widespread window screen use in Italy would likely facilitate WNV transmission. Elevated WNV transmission in the CRB may be explained by more severe drought conditions.

Finally, this chapter assessed the risk of malnutrition, migration, and mental health by examining relative poverty rates. The poverty rate in the PRB averaged 5.6%, ranging from 4.3–7.6%, and the poverty rate in the CRB averaged 14.42%, ranging from 10.73–19.4%. As poverty is a critical factor for malnutrition, migration, and poor mental health, the CRB is at a higher risk than the PRB. Poverty is also a determinant for many other illnesses such as HIV/AIDs, tuberculosis, and other infectious diseases.

As shown in Chapter 3, the CRB experienced more severe SPEI-18 and SPEI-36 than the PRB. These long-term measures of drought suggest more encompassing and comprehensive health-related challenges. This chapter evidences a greater severity of nearly all the health-related consequences of drought examined, except for air quality, in the CRB. While not as

[134] Environmental Protection Agency (EPA), "Nitrate/Nitrite Toxicity."

severe, this chapter also shows the presence of many health-related challenges in the PRB. Understanding what health-related consequences are present and most severe in a region is critical to prioritizing the most salient challenge and key public health interventions.

Chapter 5 - Conclusion

Prioritizing the salient health-related consequences of drought is the final critical step for public health practitioners and policymakers. Identifying the most salient consequences allows for a targeted, actionable, and feasible mitigation strategy.[135] Therefore, this chapter seeks to identify the most salient health-related consequence of drought among those examined in Chapter 4. The author will identify the most salient consequence based on the following criteria: number of people at risk, number of people affected, severity of the hazard, trend during the study period (increasing or decreasing), and availability of mitigation systems or policies.

The Most Salient Challenge in the PRB

As discussed in Chapter 4, the PRB experiences poor air quality and water safety, WNV, and poverty. Table 5-1 summarizes the typical severity of each health-related consequence of drought in the PRB. Poor air quality exposes and affects a wide range of the population in the PRB. Average PM_{10} concentrations in the PRB exceeded the WHO's guideline of 15 $\mu g/m^3$ by 31%, and the average $PM_{2.5}$ concentration exceeded the guideline of 5 $\mu g/m^3$ by 176%.[136] Chronic exposure to such elevated concentrations of PM, especially $PM_{2.5}$ can cause a variety of health outcomes including asthma, cancer, and heart disease.[137] Despite PM concentrations generally decreasing throughout the study period, largely due to successful regulation, air quality remains a salient challenge in the PRB.[138]

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[135] Bardach, *A Practical Guide for Policy Analysis: The Eightfold Path to More Effective Problem Solving*. p. 2

[136] WHO, "What Are the WHO Air Quality Guidelines?"

[137] Feng et al., "The Health Effects of Ambient PM2.5 and Potential Mechanisms."

[138] Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe.

Water safety similarly affects the majority of PRB residents; however, EU drinking water regulations protect both private and public drinking water supplies from nitrate and phosphorus contamination.[139] While methemoglobinemia due to nitrate consumption is a severe outcome, the elimination of nitrates from drinking water essentially removes this risk. Furthermore, regulation of agricultural fertilizer kept concentrations of nitrate in natural water bodies relatively controlled.[140] Through source control and comprehensive drinking water regulations, the PRB is protected from drought-associated water safety challenges.

WNV also poses a risk for most PRB residents. WNV infections range in severity from asymptomatic (majority of cases) to mild illness. In some cases, WNV presents with severe neurological symptoms. Over the study period, the PRB reported a cumulative WNV incidence of 8.3 cases per 100,000 residents, corresponding to 1,215 total cases. Annual WNV incidence has generally remained constant over the study period, excepting large increases in 2018 and 2022. These sporadic outbreaks may be due to the lack of population-level control measures such as window screen use or vector control. Without these control measures, WNV may represent a growing challenge in the PRB.

Finally, impoverished individuals in the PRB experience additional risk of malnutrition, migration, and poor mental health. While other groups do experience such health-related outcomes, increases associated with drought are largely due to changes in income. Therefore, an average poverty rate of 5.6% represents the proportion of households at risk of drought-associated malnutrition, migration, and poor mental health. Each of these consequences includes

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[139] European Union, Directive (EU) 2020/2184 of the European Parliament and of the Council on the quality of water intended for human consumption (recast).

[140] Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources.

a variety of health risks with a wide range of severity. The existence of social programs for impoverished individuals, such as food and income assistance, and low-cost mental health services protect against the most severe health risks. However, as poverty rates are increasing, malnutrition, migration, and mental health constitute a growing issue in the PRB.

Based on the above considerations, the most salient health-related consequence of drought in the PRB is poor air quality. Despite existing regulations, the PRB's average annual particulate matter concentrations remain well above those recommended by the WHO. While particulate matter concentrations have declined slightly over the study period, these reductions are insufficient to protect the health of PRB residents. Furthermore, air quality exposes *all* PRB residents to a variety of severe health hazards. Because poor air quality affects all PRB residents and pollutant concentrations remain elevated despite mitigation efforts, public health practitioners and policymakers in Italy should prioritize further interventions to improve air quality in the PRB.

Table 5-1; Summary of the health-related consequences of drought in the PRB.

Consequence	Measure	Average Severity
Air Quality	PM_{10} ($\mu g/m^3$)	19.72
	$PM_{2.5}$ ($\mu g/m^3$)	13.81
Water Safety	Nitrate (mg/L)	24.2
	Phosphorus (mg/L)	0.086
WNV	Incidence (cases per 100,000)	8.3
Malnutrition	Relative Poverty Rate (% of households)	5.6%
Migration		
Mental Health		

The Most Salient Challenge in the CRB

The CRB experienced the same health-related consequences of drought as the PRB in addition to the unique challenge of coccidioidomycosis. Table 5-2 summarizes the severity of the health-related consequences of drought in the CRB. As in the PRB, poor air quality affects all residents of the CRB. The average PM_{10} concentration of 19.33 exceeded the WHO's guideline by 29%, and the average $PM_{2.5}$ concentration of 6.4 exceeded the guideline by 28%. Particulate matter concentrations remained fairly constant throughout the study period, but recent updates to federal air quality standards may lead to future reductions.[141]

Related to issues of poor air quality, the CRB experienced an increased burden due to coccidioidomycosis. A majority of Valley Fever patients experience pulmonary symptoms, but the disease may present as asymptomatic or severe and chronic.[142] The CRB reported an average Valley Fever incidence of 43.5 cases per 100,000 residents, and Valley Fever incidence steadily increased over the study period. While reportable in much of the CRB, there are no existing population-level mitigation efforts. Valley Fever thus presents a growing challenge in the CRB.

In contrast to the PRB, water safety is not protected for all CRB residents. As the EPA only has regulatory oversight for public water treatment facilities, it cannot regulate private wells—on which 15% of the U.S. population relies.[143] CRB residents who rely on private wells for drinking water may thus be exposed to nitrate and phosphorus contamination as typical water treatment methods are inadequate for removing nutrients.[144] Monitors in the CRB reported an average nitrate concentration 882% higher than that allowed in treated public drinking water.

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[141] Enivronmnetal Protection Agency, "Final Rule to Strengthen the National Air Quality Health Standard for Particulate Matter Fact Sheet."

[142] Crum et al., "Coccidioidomycosis."

[143] "Domestic (Private) Supply Wells | U.S. Geological Survey."

[144] Environmental Protection Agency (EPA), "Nitrate/Nitrite Toxicity."

While individual well owners are responsible for maintaining water quality, state health departments may offer testing for common contaminants and recommendations for mitigation strategies. Despite nitrate and phosphorus concentrations decreasing in the CRB, residents who rely on private wells for drinking water may be exposed to hazardous nitrate concentrations.

WNV, however, potentially affects a wide range of CRB residents. Over the study period, the CRB reported a cumulative WNV incidence of 19 cases per 100,000 residents. WNV incidence generally decreased over the study period apart from an increase in cases in 2021. This decreasing trend may be due to vector control programs and increased awareness of WNV.

Finally, poverty in the CRB risks exposing individuals to malnutrition, migration, and poor mental health. From 2013 to 2022, the average poverty rate in the CRB was 14.4%. However, poverty rates have decreased over the study period likely due to improved assistance such as the Child Tax Credit. Even with such assistance programs, food deserts and a lack of accessible and affordable mental health infrastructure contribute to the increased burden of drought and poverty on residents' health.

Based on the above considerations, the most salient health-related consequence of drought in the CRB is coccidioidomycosis. Valley Fever poses a health risk to *all* CRB residents, and those who are infected may experience severe, chronic symptoms. Alarmingly, Valley Fever cases in the CRB *doubled* over the study period as no large-scale mitigation efforts exist. Furthermore, the geographic spread of coccidioidomycosis may further increase the burden of the disease in the CRB. Thus, public health practitioners and policymakers should enact solutions to curtail the transmission and spread of Valley Fever.

Table 5-2; Summary of the health-related consequences of drought in the CRB.

Consequence	Measure	Average Severity
Air Quality	PM_{10} ($\mu g/m^3$)	19.3
	$PM_{2.5}$ ($\mu g/m^3$)	6.4
Valley Fever	Incidence (per 100,000)	43.5
Water Safety	Nitrate (mg/L)	88.2
	Phosphorus (mg/L)	18.7
WNV	Incidence (per 100,000)	19.0
Malnutrition	Relative Poverty Rate (% of the population)	14.4%
Migration		
Mental Health		

Recommended Public Health Interventions

While the EU and Italy regulate the emission of common air pollutants, further collaboration between industry regulators and public health practitioners is needed to protect the health of PRB residents. During the study period, the annual average $PM_{2.5}$ concentration remained below the threshold regulated by the EU; however, some monitors reported a daily average concentration much higher than that recommended by the WHO.[145] Therefore, Italian public health practitioners must have systems in place to educate residents and mitigate potential health effects during times of high concentrations. The Italian government should implement an air quality warning system, such as those used to communicate severe weather, to alert PRB residents to the health risks posed by periods of poor air quality. In addition to triggering

[145] The WHO guidelines recommend a 24-hour average concentration below 15 $\mu g/m^3$, and the highest concentration reported in the PRB was 35.6 15 $\mu g/m^3$.

messaging, the alert system should indicate masking recommendations. Public health practitioners may then reduce the burden of poor air quality days by pairing such masking recommendations with increased availability of free, quality masks or respirators (e.g., free mask vending machines).

Long-term solutions are also needed to reduce the burden of poor air quality in the PRB. Currently, the EU regulates annual $PM_{2.5}$ concentrations to a concentration of 20 $\mu g/m^3$, four times higher than that recommended by the WHO.[146] While successful in improving air quality from pre-implementation concentrations, more stringent regulations are needed to further protect the health of PRB residents. Further regulations should thus aim to reduce annual $PM_{2.5}$ concentrations to 10 $\mu g/m^3$. Compliance with such regulation will be aided by further investment in renewable energy, especially given that most PRB PM pollution is driven by the use of fossil fuels.[147] One such method of renewable energy generation, hydropower, can be paired with existing water infrastructure as in the Hetch Hetchy Aqueduct of Northern California.[148] Implementing public health measures alongside further emission regulations and renewable energy investments will reduce the burden of poor air quality in the PRB.

In the CRB, control of coccidioidomycosis transmission presents a unique challenge for policymakers and is hindered by the absence of a consistent, unified reporting system. While

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[146] Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe.

[147] Perrone et al., "Sources of High PM2.5 Concentrations in Milan, Northern Italy."

[148] The Hetch Hetchy Aqueduct delivers water from reservoirs in Yosemite National Park to San Francisco and other municipal and private entities. Before treatment, water passes through two hydropower facilities. The author toured water treatment facilities along the Hetch Hetchy Aqueduct system as a part of the 41st *Frontier* Field Trip. The San Francisco Public Works Department manages the water treatment and hydropower generation along the aqueduct. Hetch Hetchy Water supplies several industrial and municipal clients, but energy produced by the aqueduct supplies municipal structures in the City of San Francisco.

nationally reportable, Valley Fever is not reportable in every state, and some health departments do not notify the CDC of Valley Fever cases. Valley Fever data is thus available for most of the CRB except Colorado and granular data (i.e., county-level) is available for only Arizona and California.[149] In this way, Valley Fever is not unlike other emerging or zoonotic public health challenges such as toxoplasmosis.[150] This lack of consistent reporting creates knowledge gaps in Valley Fever transmission and geographic distribution. To improve understanding of Valley Fever distribution and transmission in the CRB, Colorado, Nevada, New Mexico, Utah, and Wyoming should report county-level Valley Fever data to the CDC. Even with a unified, consistent reporting system, many coccidioidomycosis cases, especially those asymptomatic, will remain unreported; however, a joint, One Health reporting system may facilitate robust surveillance. Dogs are more susceptible to coccidioidomycosis than humans and, therefore, may serve as sentinels for human disease.[151] Thus, an integrated human-animal reporting system will more accurately detect Valley Fever transmission. Creating an integrated, One Health reporting system will allow public health practitioners and policymakers to better understand coccidioidomycosis transmission and design interventions.

Since it is not feasible to eliminate the risk of Valley Fever in the CRB, public health practitioners and policymakers must implement measures to mitigate exposure, infection, and severe illness. Activities that involve soil disturbance such as digging or driving heavy machinery carry the highest risk of *Coccidioides* exposure.[152] Therefore, construction workers, landscapers, and military personnel should be educated about Valley Fever and have access to

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[149] Coccidioidomycosis is reportable in Colorado, but the state does not report cases to the CDC.

[150] McCall, "Characterization of Toxoplasmosis Reporting and Surveillance in the United States."

[151] Sykes, "Animals as Sentinels: One Health Approaches to Infectious Diseases and Climate Change."

[152] Lauer et al., "Valley Fever."

free, high-quality respirators. Public health practitioners may also increase messaging and respiratory availability for the general public, especially in the months following drought. Policymakers should also explore legislation aimed at encouraging the use of dust suppressants (e.g., Bio-Dust^{TM}) or delaying new construction until the winter. In addition to reducing exposure, further investments into pharmacological interventions such as preventive vaccines and treatment options are needed to reduce the healthcare burden of Valley Fever. The development of a human or animal vaccine for coccidioidomycosis would add a critical tool available to public health practitioners, especially one that could be delivered to wild rodent populations.[153] Thus, Valley Fever may be reduced by limiting exposure to *Coccidioides* spores and investing in the development of pharmacological interventions.

Recommended Policies for Drought Resiliency

In addition to the above public health interventions, policymakers must prioritize building drought resilience through new allocation schemes, infrastructure improvements, and governance structures. Managers of both the Po and Colorado Rivers allocate water to agriculture and other industries while also meeting obligations for hydropower, drinking water, and environmental protection. Such allocations present a prominent challenge in each region, especially in the context of drought and water shortage. In both cases, reassessing water allocation schemes is a critical step in building drought resiliency. The PRB allocates water based on Water Abstraction Licenses (WALs) obtained from regional or other non-central authorities.[154] This fragmented system fails to account for changing water availability and demand.[155] Furthermore, Italy lacks

[153] Similar vaccine strategies exist for controlling plague outbreaks in wild prairie dogs.

[154] Santato, Mysiak, and Pérez-Blanco, "The Water Abstraction License Regime in Italy."

[155] Santato, Mysiak, and Pérez-Blanco.

long-term, proactive drought mitigation policies.[156] As such, water managers in the PRB would benefit from similar water allocation policies as in the CRB. CRB water allocation, while still largely based on the historic "first in time, first in place" framework, accounts for probable drought conditions. In the 2007 Interim Guidelines for the Operation of Lake Powell and Lake Mead, the Lower Colorado River Basin states (AZ, CA, and NV) agreed to receive reduced allocations based on the volume of water in Lake Mead.[157] More recently, the 2019 Drought Contingency Plan introduced voluntary allocation reductions for the Lower Basin States based on Lake Mead's volume.[158] Similar agreements in the PRB, in addition to other license restrictions, would build much-needed flexibility in Italian water allocations.[159]

As discussed above, flexibility in Colorado River water allocations is increasingly common, but allocation reform would provide further resiliency to drought. The current allocation framework in the CRB (and, in general, the American West) is that of "first in time, first in place;" essentially, entities with the oldest claim receive the most senior water right. This framework, solidified by the 1922 Colorado River Compact and complicated by a century of new claims, legislation, agreements, treaties, litigation, and re-negotiation, still serves as the basis for modern allocations. As the allocation regime evolved, however, flow rates of the Colorado River decreased from an estimated 17 MAF/year to 10 MAF/year. Therefore, water managers in the CRB must reduce allocations to meet current realities. The impending 2026 expiration of the 2007 Interim Guidelines, the 2019 Drought Contingency Plan, and the US-Mexico agreements

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[156] Santato, Mysiak, and Pérez-Blanco.

[157] Secretary of the Interior, Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead.

[158] Bureau of Reclamation, Lower Basin Drought Contingency Operations.

[159] Santato, Mysiak, and Pérez-Blanco, in "The Water Abstraction License Regime in Italy: A Case for Reform?", argue for further reforms in WALs including license time limits and requirements for efficiency.

provide ample opportunity to assess current allocations. Policymakers should consider other frameworks, such as Optimal Allocation (OA) or Harmonious Allocation (HA) to optimize allocations of Colorado River water.[160]

In the long term, PRB and CRB policymakers should invest in further infrastructure improvements including more efficient aqueducts, expanded water storage, and alternative water supplies. Both the PRB and CRB rely on large aqueduct systems to deliver river water to areas outside the basin. In Italy, these aqueducts lose, on average, 42% of their water due to leaks.[161] Such losses reflect the urgent need to rebuild and repair Italian water infrastructure, ensuring efficient use of Po River water. However, the Italian government has been slow to respond, only recently approving federal investments aimed at mending aqueducts. CRB infrastructure similarly fails to deliver much of Colorado River allocations. On average, 10% of Colorado River water evaporates and leaks from reservoirs and aqueducts.[162] New strategies and technologies, such as distance-based restrictions on allocations, are needed to protect against such losses.

Investments in new, alternative water infrastructure will also build drought resiliency by reducing reliance on river water. As the PRB, and Italy in general, has access to abundant saltwater, investment in desalination technology would reduce reliance on the Po. Desalination may also reduce Southern California's reliance on Colorado River water, especially for Los Angeles. Most of the CRB, however, is inland, and other water sources such as water recycling may be more feasible. Water recycling, the process of using treated wastewater effluent as an additional source for drinking water treatment, would facilitate reduced water allocations while

[160] Wang et al., "A Compound Cloud Model for Harmoniousness Assessment of Water Allocation."

[161] Italian National Institute of Statistics, "ISTAT Water Statistics (2018-2020)."

[162] Naishadham, "In the West, Pressure to Count Water Lost to Evaporation."

ensuring a more stable, safe drinking water supply. Because wastewater effluent is so clean—often cleaner than surface water—integration with existing drinking water treatment would only require simple infrastructure to deliver the effluent to treatment facilities with no additional treatment processes.[163] By investing in updated, future-proof infrastructure and alternate water supplies, governments can build more efficient water delivery systems and improve drought resilience.

Furthermore, the complex governance structure of Colorado and Po river water hinders timely response to drought conditions. Management of both basins involves a fragmented, polycentric hierarchy of international, national, regional, and municipal entities across many sectors (hydropower, drinking water, industry, agriculture, and environmental management).[164] This complex structure presents several barriers to efficient management. First, the lack of sector integration creates challenges in holistically managing the basin with consideration of its many uses. Second, the fragmented governance structure impedes centralized efforts of water management and generates confusion and lengthy litigation processes. Finally, siloed management encourages zero-sum thinking and inhibits effective collaborative governance.[165] The creation of a centralized, collaborative, and adaptive governance structure would facilitate sector integration and reduce delays in adapting to drought.

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[163] Kloster, Interview.

[164] Manieri, "The Po River Basin: Managing a Complex System"; Sullivan, White, and Hanemann, "Designing Collaborative Governance."

[165] Ackleson, Interview.

Future Directions

This inductive thesis sought to provide a critical first step in understanding the health-related consequences of drought in the PRB and CRB. In doing so, this thesis generated several avenues for future, deductive research. In particular, further study, both quantitative and qualitative, is needed to assess the association between drought and malnutrition, migration, and poor mental in Europe and the United States. Researchers, public health practitioners, and policymakers also require more granular geographic (e.g., county level) and temporal (e.g., monthly) data to further test the association between drought and its health-related consequences and develop corresponding action plans. Such data will be critical for the PRB, CRB, and the global community as droughts become more common and severe in the era of climate change. However, public health practitioners and policymakers need not wait for such deductive studies. The health hazards this thesis inductively assesses present urgent challenges in both the PRB and CRB. Implementing solutions such as those proposed above will mitigate these hazards and protect the health of PRB and CRB residents.

As is exemplified in this thesis, droughts are global phenomena with a wide range of environmental, economic, social, and health challenges. These challenges vary with geography and existing policies. Comparative analyses such as this work are critical in understanding the effects of droughts in different geographies and inductively assessing possible strategies and policies that may mitigate the effects of drought. In that spirit, increased international, integrated, and intersectoral collaboration will be the cornerstone of any successful effort to protect against the health-related consequences of drought.

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