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Perspectives on Water Resources Risk, Policy, and Stewardship

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**PERSPECTIVES ON WATER RESOURCES RISK, POLICY, AND
STEWARDSHIP**

By

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A DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy
(in Civil Engineering)

The Graduate School
The University of Maine
May 2019

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PERSPECTIVES ON WATER RESOURCES RISK, POLICY, AND STEWARDSHIP

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An Abstract of the Dissertation Presented
in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy
(in Civil Engineering)
May 2019

Water management approaches have historically optimized water for human use and placed lower emphasis on the relationship between ecosystems and humans. Despite efforts to balance human and ecosystem needs, existing management approaches tend to prioritize some needs, knowledges, and values over others. Natural and anthropogenic changes pose challenges to water governance institutions due to policy inflexibility, and may lead to ecosystem degradation, water stress, and conflict among water users.

This work seeks to redress these shortcomings through three scholarly contributions. First, a conceptual framework for Water Resources Stewardship is developed in support of equitable and adaptive solutions under changing conditions. Key elements include attention to the structure of governance, opportunities for stakeholder inclusion, knowledge production and use, and adapting to changes in risk. A meta-analysis of prominent water sector approaches identifies gaps and informs future perspectives. Next, a historical analysis of Maine's in-stream flow policy is presented. The analysis approach comprises of a) delineation of the rulemaking structure including the sequence and co-evolution of processes therein, b) characterization of events and conditions leading to rulemaking, and c) identification of opportunities and constraints to integrate adaptive policymaking in a water use context undergoing change. Opportunities for learning, integration of diverse stakeholder needs, and infusion of knowledge are needed to enable adaptive processes.

Lastly, methodological advancements for assessing precipitation change enables a reassessment of risk to human and ecological systems. A quantile regression approach is used to a) assess annual precipitation relationships with oceanic indices at river basin scales, and b) identify asymmetries with mean precipitation trends at the global scale. Notably, significant land area and populations are overlooked by conventional methods. An extension to rainfed agriculture underscores the need for more accurate appraisal of change and uptake into risk management approaches.

DEDICATION

To my family: those near and far in both space and time

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TABLE OF CONTENTS

DEDICATION ii

ACKNOWLEDGEMENTS iii

LIST OF TABLES ix

LIST OF FIGURES xi

1. INTRODUCTION 1

2. WATER RESOURCES STEWARDSHIP IN AN ERA OF RAPID CHANGE 9

 2.1 Chapter Abstract 9

 2.2 Introduction 9

 2.3 Principles of Water Resources Stewardship 13

 2.3.1 Linkages Across Scales 14

 2.3.2 Inclusion of Place, Peoples, and Values 16

 2.3.3 Diverse Knowledges 17

 2.3.4 Governance and Institutions 20

 2.3.5 Co-produced Solutions 22

 2.3.6 Adaptive Risk Management 24

 2.3.6.1 Systems-level View of Stewardship 28

 2.4 IWRM: From Concept to Practice 28

 2.4.1 IWRM Case Methodology 29

 2.4.2 IWRM Themes Across Regions 30

2.4.3	Theme 1: Balancing Human and Environmental Objectives	31
2.4.4	Theme 2: Public Participation and Inclusion	33
2.4.5	Theme 3: Monitoring and Appraising Outcomes	36
2.5	Appraisal of IWRM from a Stewardship Perspective	37
2.6	National-level Indicators on the Global Scale to Inform Stewardship	40
2.6.1	Selected National-Level Indicators	40
2.6.2	Externalities to Systems: The Case of Virtual Water Trade.....	42
2.7	Summary and Conclusions	44
3.	ADAPTIVE POLICY IN TIMES OF CHANGE: MAINE’S ENVIRONMENTAL FLOW RULE	47
3.1	Chapter Abstract	47
3.2	Introduction	48
3.3	The Maine State Context	50
3.3.1	Physical Background	50
3.3.2	Governance Background	51
3.4	Driving Factors of Policy Action.....	54
3.5	Maine Chapter 587 Rulemaking	54
3.5.1	Pre-Rulemaking.....	55
3.5.2	Rulemaking	56
3.5.2.1	Governance Structure and Existing Rules.....	59
3.5.2.2	Knowledge Acquisition.....	62
3.5.2.3	Stakeholder Participation.....	64
3.5.2.4	Agency Responsiveness	66

3.5.2.5	Legislative Action	67
3.5.2.6	Implementation.....	68
3.5.3	Post-Rulemaking	68
3.6	Conclusions.....	70
4.	DIVERSITY OF GLOBAL PATTERNS OF PRECIPITATION VARIABILITY AND CHANGE ON RIVER BASIN SCALES: A CONDITIONAL QUANTILE APPROACH.....	73
4.1	Chapter Abstract	73
4.2	Introduction.....	74
4.3	Data and Methods.....	77
4.3.1	Data and Study Region	77
4.3.2	Annual Precipitation Variability and Change: Conditional Quantile Functions.....	78
4.3.3	Distributional Characterization of Synthetic Data	79
4.3.4	Changing Perspectives of Conditional Risk.....	80
4.3.5	Basin-Scale Distributional Changes	81
4.4	Results.....	82
4.4.1	SST-Precipitation Relationships.....	82
4.4.2	Variability in Quantile-Specific SST-Precipitation Relationships	84
4.4.3	Combinations of Upper and Lower Precipitation Quantile Responses	86
4.4.3.1	Africa	88
4.4.3.2	Australia and Southeast Asia	88
4.4.3.3	Asia	88

4.4.3.4	Western Europe	89
4.4.3.5	Eastern Europe and Russia.....	89
4.4.3.6	South America	89
4.4.3.7	North America	89
4.4.4	Assessment of Distributional Variability and Conditional Risk	90
4.5	Summary and Conclusions	93
5. OVERLOOKED TRENDS IN GLOBAL ANNUAL PRECIPITATION		
	REVEAL UNDERESTIMATED RISKS	96
5.1	Chapter Abstract	96
5.2	Introduction	96
5.3	Trend Assessment Over the Entire Range of Variability	97
5.4	Data and Methods	99
5.4.1	Data Selection and Processing	99
5.4.2	Precipitation Data Quality.....	99
5.4.3	Trend Calculation with Wild Bootstrap	100
5.4.4	Trend Typology.....	101
5.5	Global Reassessment of Precipitation Trends at Specified Thresholds	101
5.6	Typology of Precipitation Variability and Risk.....	103
5.7	Overlooked Trends in Rainfed Agricultural Systems	106
5.8	Implications of Mischaracterized Trends for Risk to Human and Environmental Systems	108
6.	CONCLUSION.....	110
	REFERENCES	115

APPENDIX A – SUPPLEMENTAL MATERIAL FOR CHAPTER 2.....	143
APPENDIX B – MAINE CHAPTER 587: IN-STREAM FLOWS AND LAKE AND POND WATER LEVELS	151
APPENDIX C – SUPPLEMENTAL MATERIAL FOR CHAPTER 3.....	169
APPENDIX D – SUPPLEMENTAL MATERIAL FOR CHAPTER 4.....	178
APPENDIX E – QUANTILE-SPECIFIC PRECIPITATION RESPONSES TO SST VARIABILITY ON CONTINENTAL SCALES	186
APPENDIX F – SUPPLEMENTAL MATERIAL FOR CHAPTER 5	197
BIOGRAPHY OF THE AUTHOR	207

LIST OF TABLES

Table 2.1	IWRM Thematic Keywords.....	29
Table 2.2	Regional Appraisal of IWRM Case Studies.....	35
Table 2.2	Regional Appraisal of IWRM Case Studies (Continued)	36
Table 3.1	Select Federal and State Water Management Agencies and Organizations (pre-2012)	53
Table 3.2	Chapter 587 Seasonal Aquatic Base Flow Standards	63
Table 3.3	Stakeholder Groups Involved in Chapter 587 Rulemaking.....	65
Table 4.1	Conditional Quantile Response for the Chad River Basin	92
Table C.1	Key events in Maine Chapter 587 Rulemaking	173
Table C.2	Selected Environmental Flow Assessment Approaches.....	174
Table C.2	Selected Environmental Flow Assessment Approaches (Continued)	175
Table C.2	Selected Environmental Flow Assessment Approaches (Continued)	176
Table C.3	Characteristics of USGS Flow Equation Reports for Maine	177
Table D.1	Pearson Correlation Coefficient of Precipitation and SST EOFs	181
Table D.2	Change in Probability Across Selected Quantiles Over Time.....	184
Table E.1	Regression Coefficients ($\tau = 0.2, 0.8$) for SST Covariates Across Selected Basins.....	196

Table F.1	Global Significant Precipitation Trend Patterns Across Quantiles for Positive, Negative, and Non-significant Trends in LR.....	205
Table F.2	Rainfed Land Types Across Regions.	206

LIST OF FIGURES

Figure 2.1	Key elements of the Water Resources Stewardship framework	14
Figure 2.2	Water Resources Stewardship within a systems context.	27
Figure 2.3	IWRM case study timeline.	30
Figure 2.4	Frequency of themes and keywords in select IWRM studies by region	32
Figure 2.5	Appraisal of IWRM from a Water Resources Stewardship Lens	38
Figure 2.6	Relationship between the leading statistical pattern of governance and blue and green virtual water flux	43
Figure 3.1	Timeline and relative importance of activities for the Chapter 587 rulemaking process.....	58
Figure 3.2	Jurisdiction of selected federal and state agencies for water quality and quantity management relating to Chapter 587.....	60
Figure 4.1	Quantile regression of synthetic precipitation data(mm) conditioned on time ($\tau = 0.2, 0.5, 0.8$) highlights the diversity of changes in environmental data.	80
Figure 4.2	Leading statistical patterns of precipitation and sea-surface temperature.	83
Figure 4.3	Spatial distribution of precipitation trends conditioned on years 1950-2011, EOF1 and EOF2.	85
Figure 4.4	Typology of basin-scale precipitation sensitivity to climate variability and change.	87

Figure 4.5	Precipitation quantile position changes for possible EOF1, EOF2 values in the Chad River Basin, Africa.....	91
Figure 5.1	Tail trends show inconsistencies with mean and median.....	102
Figure 5.2	Trends in tails show asymmetries in sign, magnitude, and spatial distribution.....	103
Figure 5.3	Tail typology combines dry and wet tail trends to synthesize variability and risk of precipitation excesses and deficits.	104
Figure 5.4	Overlooked trends coincide with regions dominated by rainfed agriculture.....	107
Figure A.1	Percent difference between Blue and Green virtual water exports and imports.....	147
Figure A.2	Worldwide Governance Indicators 2016.....	148
Figure A.3	Global WGI PCA variance explained.....	149
Figure A.4	Second leading statistical pattern of WGI and correlation with corresponding indicators.....	149
Figure A.5	Regional statistical leading patterns of worldwide governance indicators.....	150
Figure C.1	Historical streamflow trends (1950-2016) for unregulated Maine streams.....	169
Figure C.2	Rulemaking process in Maine.....	172
Figure D.1	River basins from “405 major water basins of the world” obtained from the Global Runoff Data Centre (GRDC) used in analyses.....	179

Figure D.2	Average percentage of annual precipitation (1951 – 2011) occurring in each month.	180
Figure D.3	Global patterns of total annual precipitation weighted by latitude.	182
Figure D.4	Comparison of changes implied by QR and LR for synthetic data.	184
Figure D.5	Spatial distribution of weighted basin-level precipitation response.	185
Figure F.1	Linear quantile regression coefficient estimates over the full range of quantiles (τ) for two sample locations in North America.	198
Figure F.2	LR mischaracterizes risk at thresholds in the upper and lower tails of the annual precipitation distribution.	199
Figure F.3	Assessment of trends in annual precipitation conditioned on the long-term mean precipitation totals.	200
Figure F.4	Annual definition impacts annual totals.	202
Figure F.5	Correlation coefficient of annual precipitation time-series (1950 - 2011) NOAA PREC/L and CRU TS4.01 datasets at 0.5 x 0.5 degree resolution.	203
Figure F.6	Lag 1 autocorrelation of annual precipitation trends (1950-2016).	204

CHAPTER 1

INTRODUCTION

Water is an essential component of the human-environmental system supporting health and well-being. A range of human systems depend on freshwater availability including agriculture, energy systems, industry, domestic water supply, recreation, and various cultural and spiritual practices. Water underlies ecosystem functioning, enabling the provision of a range of benefits including natural resource provision, soil formation, nutrient cycling, climate regulation, habitat creation, flood attenuation, and water quality control functions (Brauman et al., 2007). As such, ecosystems and human health and well-being are closely linked, with people relying upon ecosystems for a range of benefits. However, water management approaches have historically relied on technical knowledge and engineering approaches that prioritize human water use while addressing environmental water needs through the provision of minimum flow levels leading to stressed ecosystems (Postel and Richter, 2003). For example, both diversion of water from rivers and land reclamation projects to support agricultural expansion has led to land-use change, water quality and quantity declines, and loss of wetlands and other natural habitats. Richards (1986) notes that this alteration of the landscape over time has changed the spatial distribution of development and promoted socioeconomic development. However, the benefits and environmental ills of these interventions have not been equitably distributed across peoples and place (Agyeman et al., 2016). For example, indigenous populations and natural resource dependent communities are especially impacted by ecosystem degradation (Robinson, 2016) with over-extraction of surface water and quality declines negatively impacting subsistence fishing and cultural practices (Finn and Jackson, 2011). A lack of attention to how people interact with the environment in diverse ways may result in management strategies that are ineffective as well as inequitable. An acknowledgement of

these shortcomings has prompted efforts towards management approaches that harness synergies among people and the environment (Kates et al., 2001, e.g).

Key elements of more comprehensive approaches include participatory decision-processes (Reed, 2008), building the capacity of underrepresented populations (Gallopín, 2006), use of knowledge to inform and support policies (Berkes, 2009; Armitage et al., 2011), a broader consideration of the relationship between water and the environment (Poff et al., 1997; Postel and Richter, 2003), and a focus on meeting basic human needs (Millennium Ecosystem Assessment, 2005). However, critically absent from contemporary approaches is an explicit acknowledgement of equity beyond the distribution of environmental benefits and ills (Friedman et al., 2018). For example, drought risk is experienced in materially different ways across peoples (Renn, 2011). Risk is constituted as the combination of likelihood and consequence. While the likelihood of experiencing decreased precipitation may be the same for two farmers, the farmer who has access to water storage infrastructure or climate forecasting tools will experience the effects of a drought differently than the one who lacks access to alternatives. A policy designed to mitigate the impacts of drought may fail to identify and address the needs of those who lack the capacity to participate within policy processes. As such, equity encompasses a) the inclusion of people in decisions that affect their livelihoods, and b) the respect of peoples, their views, and needs within decision processes.

Complicating matters, water management has historically assumed unchanging hydrologic conditions, with infrastructure and policies often ill-equipped to address changing baselines (Holling, 1978). Land-use and landscape alteration, demographic transitions, emerging water user groups, changing water needs, and increased likelihood of hydroclimatic extremes may all render management strategies ineffective. Furthermore, the scales at which these changes occur are often mismatched with management interventions, often resulting in piecemeal approaches to complex problems (Young, 2008). While water management efforts have placed an emphasis on increased monitoring and adaptive

approaches to reduce risks to human and environmental systems, the policies designed to guide management may effectively expire due to changing conditions. Thus, adaptive policies are necessary to anticipate and navigate human and environmental change and mitigate risk (Swanson et al., 2010).

These shortcomings underscore the need for approaches that can a) appraise existing management arrangements and b) support the development of equitable and adaptive solutions for sustainable outcomes. This work seeks to fill these gaps in three ways:

1. The development of a new conceptual framework to support equitable and adaptive solutions under changing conditions. Existing disciplinary approaches and international-level goals for water management are synthesized to inform a novel and integrative approach to water resources management. Regional meta-analysis of Integrated Water Resources Management – a prominent water sector approach – is used to inform the framework and identifies common themes, opportunities, and shortcomings across cases. Statistical analysis of water-based and governance indicators further informs perspectives on vulnerability at the global scale.
2. The delineation of a place-based environmental rulemaking process to identify opportunities and constraints for adaptive policy development. A historical retrospective of Maine’s statewide environmental flow rule is conducted through review of rulemaking documents, legislative records, and scientific reports. The process is decomposed into key components to characterize how interactions among elements may impede or promote rule development. Adaptive policy requires opportunities for learning and mechanisms for knowledge integration. Identification of the conditions and events leading to rulemaking and challenges in the post-rulemaking time frame point to opportunities for integrating adaptive policy-making into existing institutions and procedures.

3. Advancement of statistical methodology for assessing precipitation and risk to social-environmental systems. Annual precipitation changes are assessed at both the global and river basin scales using a quantile regression approach (Koenker and Bassett, 1978). Quantile regression (QR) enables detection of a diversity of change across the precipitation distribution where commonly-used methods assume symmetric change with the mean. Precipitation sensitivity to climate-based indices enables a more accurate assessment of precipitation variability and change. Global land areas, population, and rainfed agricultural areas with precipitation trends undetected or mischaracterized by mean trends are also identified underscoring the implications of underestimating risk. Application of the methodology to sector-specified precipitation levels offers a more comprehensive assessment of risk and may be used to inform adaptation strategies.

Additional details and a summary of each chapter follows.

Chapter 2 presents a framework for Water Resources Stewardship: the shared human responsibility and care for the environment under changing conditions, promoting inclusion and respect of peoples, values, knowledges, and diverse ecosystem interlinkages for the shared production of solutions to support equitable and sustainable futures. An overview of existing water resources challenges is presented, with aspirational goals and different disciplinary approaches highlighted. Next, the framework for Water Resources Stewardship is delineated and presented. The framework decomposes the social-ecological system into a series of interconnected elements: interlinkages across scales, inclusion of peoples, places, and values, diverse knowledges, governance and institutions, co-produced solutions, and adaptive risk management. Taken together, explicit acknowledgement of these elements enables a broader consideration of equity in decision-making and risk perspectives. Special attention is provided to governance structure. Governance is the assemblage of institutions that moderate how people interact with the environment and each other. These institutions, including rules, regulations, and social norms, structure how management

decisions are made and may result in processes and outcomes that privilege some peoples, knowledges, and values over others. Therefore, governance structure has implications for equity and adaptation. The framework is used to appraise Integrated Water Resources Management (IWRM) - a prominent water management approach that has been applied globally at national and river basin scales. A UN Sustainable Development Goal, IWRM is highly promoted for its focus on integration of water sectors, balance between economic, social, and environmental outcomes, and sustainability. However, a lack of documented success suggests weaknesses in its implementation (Biswas, 2004). A meta-analysis of IWRM case studies is conducted to underscore the saliency of Stewardship; enabling comparison across communities while being responsive to local contexts. As few cross-comparisons of IWRM cases exist, this synthesis also fills a knowledge gap regarding commonalities and unique features among cases regionally. Statistical analysis of water-based and governance indicators is also conducted to illustrate the shortcomings of contemporary approaches regarding externalities. Water Resources Stewardship organizes and fortifies existing disciplinary knowledges and enables progress towards sustainability solutions that are adaptable and equitable.

Chapter 3 seeks to identify opportunities for adaptive policy within a place-based environmental rulemaking context. Environmental flows refer to the quantity of water needed to sustain ecosystems, and can be constituted by characteristics of magnitude, timing, frequency, duration, and rate of change. Environmental flow rules set standards for flow alteration that when exceeded result in ecological degradation, water stress, and conflicts among users. However, these rules lack flexibility and may be rendered ineffective due to changing uses and climatic conditions. Identifying opportunities for learning and triggering action is necessary for creating an adaptive policy environment. A historical retrospective of the State of Maine *Chapter 587: In-stream flows and lake and pond water levels* is presented. An analysis approach consisting of a delineation of the rulemaking structure including the sequence and co-evolution of processes is used to a) understand how

governance context may enable or disable a broader integration of objectives, values, and knowledges and b) identify opportunities to facilitate compromise and interventions that support adaptation. Externalities that act as ‘focusing events’(Birkland, 1998) to prompt policy action and instances of tensions among stakeholder, existing regulations, and constraints to integrating scientific information are also discussed. While only a single instance of an institution, the Ch. 587 development process fills an existing knowledge gap for water policy processes in Maine and offers insights to inform future rulemaking.

As noted above, stewardship draws attention to the ways in which risks are understood, anticipated, and managed. How change in hydrologic systems is characterized has importance for a) identifying risks to systems and b) informing adaptation strategies. Chapters 4 and 5 present methodological advancements for characterizing change and likelihood in order to inform more comprehensive risk management approaches. Precipitation is a primary component of the global water budget and is closely tied to a range of human-environmental systems, including agriculture (Hatfield. et al., 2014) and water supply (Vörösmarty et al., 2000). These systems are sensitive to precipitation at various thresholds - precipitation levels that when exceeded pose consequences to a system (Guntenspergen, 2014). The likelihood of exceeding specified thresholds is therefore an important component of risk assessment. However, widely-applied linear regression based approaches assume a) the change in mean conditions is representative of changes across all thresholds and b) variance is unchanging, which is not borne out in environmental data. Through use of a quantile regression (QR) model (Koenker and Bassett, 1978), this work characterizes annual precipitation change across the entire probability distribution function (PDF) enabling a more comprehensive approach for quantifying risk. Trends are characterized at a user-specified quantile τ which corresponds to the precipitation level where τ proportion of the data are exceeded. Trends can be assessed across all τ of the PDF enabling a more comprehensive assessment of change in risk and variability.

Chapter 4 demonstrates the flexibility of the quantile regression approach over widely-used linear regression-based methods through analysis of synthetic precipitation data. Then, trends in annual precipitation (1950-2011) are assessed at river basin scales - a scale that is frequently used for water resources planning (Global Water Partnership, 2000, e.g.). Regional sensitivity of trends to the phase and magnitude of the leading statistical patterns (Jolliffe, 2002) of global sea-surface temperature (El Niño-Southern Oscillation and Atlantic Multidecadal Oscillation) are identified. Finally, an approach for quantifying risk across specified precipitation thresholds is demonstrated. Annual precipitation trends (1950-2017) at quantiles representing high and low precipitation levels are compared with mean trends in Chapter 5, revealing locations where risk is mischaracterized or undetected by LR. These trends are then intersected with global land area and population identifying the spatial extent and exposure to overlooked trends. A case study for rainfed agriculture - a sector highly sensitive to precipitation change - illustrates the utility of assessing trends at different thresholds. These methodological advancements in characterizing risk may be harnessed within a Water Resources Stewardship approach to assess hydroclimatic change at more appropriate targets for informing adaptation strategies. Finally, key conclusions and lines of inquiry for future work are discussed (Chapter 6).

Taken together, this work offers a new approach to managing water resources in an equitable and adaptive manner. The Water Resources Stewardship framework fills a gap in existing approaches by reorienting the conceptualization of human-environmental relationships. More explicit attention is brought to how the structure of governance moderates this relationship and works to enable or disable a broader integration of objectives and outcomes. Chapter 2 further explores this dynamic through a historical retrospective of Ch. 587 - a process borne out of the need for balance between human and ecological objectives. Delineation of the rulemaking process provides an important contribution for informing future opportunities to integrate adaptive elements into policies. Methodological advancements in characterizing hydroclimatic change at scales critical to

water resources management further enable the consideration of risk across a range of thresholds to better inform adaptation strategies (Chapters 4 and 5).

CHAPTER 2

WATER RESOURCES STEWARDSHIP IN AN ERA OF RAPID CHANGE

2.1 Chapter Abstract

Natural and anthropogenic changes in the earth system impacts human and environmental well-being. Water, as a critical component of social-environmental systems, has historically been managed in a way that prioritizes water supply and flood control; some side-effects include stressed ecosystems, water quality declines, and inequitable access to water. The pervasive nature of water issues, both emerging and persistent, reiterate the need for systematization of knowledge and re-envisioning of place-based planning and management of water systems. Here a new conceptual framework for Water Resources Stewardship with a focus on equitable and adaptive solutions under changing conditions is developed. This framework organizes and fortifies existing knowledge and presents a systems-level view resolved at national and watershed scales. Regional meta-analysis of Integrated Water Resources Management (IWRM) and national-level indicators identifies shortcomings in current approaches and informs opportunities for integration of a stewardship approach. Our approach underscores the need for re-conceptualization of the human-environment relationship. The resulting focus is an adaptive and equitable approach that embraces risk-based approaches to steward water systems within an uncertain and changing environment.

2.2 Introduction

Water is an integral component of the social-environmental system, underlying the health and functioning of ecosystems and supporting human health and well-being. Water is critical to human systems such as agriculture, energy systems, and water supply while also sustaining ecosystems that support a range of benefits including resource provision,

climate regulation, water quality enhancement, soil formation, flood attenuation, and cultural and spiritual values (Brauman et al., 2007). However, water provision to support human systems has often been prioritized at the expense of ecosystem health, discounting both its intrinsic value and the diversity of ways in which ecosystems relate to human well-being (UNDP, 2011). Water management has traditionally relied upon engineering and technical knowledge to optimize water provision for prioritized uses, assuming unchanging hydroclimatic conditions. For example, through the 20th century in the United States, dam operations prioritized agriculture, flood control, industry, and water supply while addressing environmental health through minimum flows for fish species of economic or recreational importance (e.g. Tennant, 1976; Palmer and Snyder, 1985). Landscape, demographic, and hydroclimatic changes outside the predictability of planning have contributed to environmental degradation, biodiversity loss, and water supply issues prompting efforts to better balance human and ecosystem needs.

Recognizing the feedbacks between people and the environment, sustainability science has promoted a re-conceptualization of human-environment interactions, advocating for a balance between meeting human needs and ensuring the integrity of earth's life support systems both now and in the future (Kates et al., 2001). Consistent with this goal, approaches have sought to consider a broader range of human-environment interactions and trade-offs, changing baselines, and the inequities in how people experience the benefits of ecosystems and the impacts of degradation and hazards. In 1977, The United Nations (UN) Water Conference drew international attention towards the challenge of meeting water demands in the future, highlighting issues of efficiency, quality, quantity, relationships with global food supply, human health, and natural hazards (Falkenmark, 1977). Aspirational goals for water have subsequently been put forth on the global stage including:

- a) The Dublin Statement on Water and Sustainable Development (1992) which i) recognizes water as a finite resource essential to life, ii) calls for participatory

approaches, iii) emphasizes the role of women in managing water, and iv) puts forth water as an economic good.

- b) The Brisbane Declaration on Environmental Flows (2007) which recognizes that the alteration of streamflow due to human activity and climatic changes threatens ecosystems, calls for i) the integration of environmental flows into land and water management, ii) participatory approaches to engage all stakeholders, iii) increased institutional capacity to scientifically monitor ecosystems, iv) increased capacity for peoples to participate in decision-making, v) adaptive approaches to monitor and refine policy actions.
- c) The Bonn Declaration on Global Water Security (2013) which calls for i) multi-scale and interdisciplinary approaches to water science, ii) integrated approaches to inform risk assessments, iii) expanded monitoring of water systems, iv) consideration of ecosystem-based alternatives to hard infrastructure, and v) a balance of governance and technical solutions that consider value systems and equity.

These declarations constitute some of the agreed upon broad-based goals for water resources management, often linked to co-evolving initiatives regarding human development such as the UN Millennium Development Goals and recent Sustainable Development Goals (SDGs).

Parallel to the development of these declarations, knowledge and approaches seeking to understand human relationships with the environment, including water, have been organized in various disciplinary arenas. For example, socio-hydrology (Sivapalan et al., 2014) and water security (Vörösmarty et al., 2010; Srinivasan et al., 2017) constitute emerging efforts to integrate traditional engineering and hydrology approaches with broader human-environmental systems framings. These approaches are briefly summarized in Online Resource 1. Integration of disciplinary approaches with development efforts such

as the SDG initiatives is ongoing. Water security (UN-Water, 2013) and its relationship with food and energy, known as the water-food-energy nexus (Food and Agriculture Organization of the United Nations, 2014), are prominent examples. One instance is the vulnerability of rainfed agricultural systems to precipitation changes with implications for food security in regions throughout the world (Lausier and Jain, 2018a).

On an ongoing basis, the pervasive nature of the societal reliance on water resources offers myriad examples of outcomes from current piecemeal approaches – mismanagement of scarce water resources, episodes of environmental quality declines, and inequities that sometimes result in conflicts – throughout the world. Among comprehensive approaches that seek to redress recurrent issues, Integrated Water Resources Management (IWRM) has emerged as the dominant paradigm for water resources management on the global scale. Expanded on in later sections, IWRM is closely aligned with aspirational goals for development, has been adopted into legislation, and is a component of the SDGs (Target 6.5). However, Biswas (2004, 2008) has noted that IWRM lacks a clear framework for operationalization due to its broad-based definition and objectives while Medema et al. (2008) underscore a lack of evidence regarding its effectiveness. Likewise, Narain et al. (2017) points to the deficiencies of traditional approaches in addressing relationships between state government structure and water users. Despite these concerns, its implementation is likely to continue, offering a vantage point for understanding the current state of water governance. Therefore, reappraisal of IWRM is necessary to identify key features, shortcomings, and knowledge gaps to inform new approaches in an era of rapid change.

In an effort to reorganize existing knowledge and address equity in a more comprehensive and transparent manner, Water Resources Stewardship is presented. Here it is defined as: the shared human responsibility and care for the environment under changing conditions, such that inclusion and respect of peoples, values, and knowledges, and diverse ecosystem interlinkages are promoted for the shared production of solutions in support of

equitable and sustainable futures. Stewardship delineates the dynamical components of the social-environmental system and seeks to fortify place-based sustainability solutions: ones that are adaptive and equitable. In what follows, Water Resources Stewardship is presented as a multi-disciplinary, salient, and responsive approach. To illustrate the opportunities for stewardship to fill gaps in existing approaches, IWRM offers a ready context for appraisal. Despite its ubiquity, few regional cross-comparisons of IWRM cases exist. A quantitative content analysis and regional comparison of selected IWRM case studies is conducted to identify priorities of the current IWRM discourse, implementation gaps, and emerging opportunities, thus informing stewardship perspectives. Finally, stewardship is briefly considered as an approach towards addressing problems with multiple human and environmental objectives in the face of changing social and environmental conditions.

2.3 Principles of Water Resources Stewardship

In this area of rapid anthropogenic change, a critical imperative is to address human and ecological well-being in an equitable manner. A weakness in many existing approaches is a fragmented view of equity; frequently limited to final outcomes of efforts expressed as socio-economic indicators of well-being or in terms of procedural elements of decision-making. Reviews of existing conservation literature indicate that limited attention is paid to a) the prioritization of some needs while overlooking others, and b) recognizing the validity of different identities (e.g. Friedman et al., 2018). With an ethic of care and respect for diverse human-environmental relationships at its center, stewardship aims to enable equity on an ongoing basis by delineating the components of the social-environmental system (SES). This requires special attention to inclusion of peoples, their values, perspectives, knowledges, and institutionalized processes for solution co-production. While the interlinked nature of complex systems can impede the deconstruction of systems into smaller parts (Gell-Mann, 2010), there are a spectrum of examples of SES complexes that are not decomposable but can still be disentangled and

organized into knowledges around systems. Stewardship thus broadens the representation of system elements while acknowledging their interlinked nature. To respond to perturbations and changes both external and internal to the SES, stewardship is iterative, recognizing the reflexive relationships among governance, infrastructure, environmental degradation, and economic activity that may surpass delineated scales of management – an important consideration in a globalized world. To this end, the SES into six related but distinct elements within the stewardship approach: a) interlinkages across scales, b) inclusion of place, peoples, and values c) diverse knowledges, d) governance and institutions, e) co-produced solutions, and f) adaptive risk management (Figure 2.1).

2.3.1 Linkages Across Scales

The range of ecosystem functions and human uses supported by hydrologic systems calls for a more comprehensive acknowledgement of the interlinkages and trade-offs in how people interact with the environment. Healthy and functioning ecosystems sustain a range of functions that contribute to human systems such as soil formation, water filtration,



Figure 2.1: Key elements of the Water Resources Stewardship framework

nutrient cycling, carbon sequestration, and flood attenuation (Brauman et al., 2007). Prioritization of a subset of benefits such as economic growth or human health and safety often leads to consequences that undermine those very objectives, limit access to other benefits, or affect people in other places. For example, decisions to divert surface water for irrigation may increase food security and support economic growth in the short-term but can also lead to downstream flow alteration impacting aquatic habitats, wildlife, the production of resources, and people. Dasgupta (2014) notes that prioritization of resources leads to inappropriate spatial and temporal trade-offs, such as upstream exploitation leading to shortages downstream and degradation of ecosystems, limiting options in the future. While exploitation of groundwater sources often serve as an alternative to surface water, failure to consider the interlinked nature of the hydrologic system may exacerbate existing and future reductions in streamflow. Likewise, the failure to consider the effects of decisions in other sectors can reverberate throughout a system. For example, timber constitutes an important resource-base, but logging practices can cause reduction in rainfall infiltration, increased soil erosion, reduced water quality downstream, and changes in streamflow posing potential impacts to aquatic habitat, drinking water, and agriculture (e.g. Winkler et al., 2017). Alteration of landscapes may threaten components of human well-being such as sense of place, identity, and practices associated with a way of life. Therefore, how people assess the trade-offs among management actions impacts both the well-being of people and ecosystems across space and time.

While broader conceptions of human-environmental interactions drive the foundation of the human-environmental systems literature, trade-offs among objectives often incorporate economic valuation or preference (Tallis and Polasky, 2009). Concerns that are difficult to quantify or environmental benefits that are under-appreciated, may be subsequently undervalued. When the range of human-environmental interlinkages are narrowly conceived, these concerns are further heightened as efforts to address well-being may be reduced to economic or development objectives, masking benefits valued by voices outside

of formal decision-making spheres (Van Assche et al., 2017). Therefore, considering a broader array of linkages sets a foundation for equity, as optimizing a few objectives at the expense of ecosystem health inherently privileges some and harms others. Acknowledging these interlinkages enables a) a broader conception of human well-being, b) identification of synergies with other objectives, and c) more comprehensive evaluation of trade-offs.

2.3.2 Inclusion of Place, Peoples, and Values

Prioritization of a subset of environmental-human interlinkages has often been accompanied by a lack of inclusive decision-making processes. While there is recognition of the benefits of including stakeholders and citizens in decision-making, such as increasing policy ‘buy-in’ and ensuring management actions are acceptable to a broader array of people (National Research Council (NRC), 2004), access to processes and the capacity to participate varies. Participation processes have often prioritized stakeholders from economically and socially valued sectors such as agriculture, industry, municipal supply, and energy systems in part due to narrow framings of human-environmental interlinkages and objectives (Jackson, 2006). These processes range from consultative to collaborative (Reed, 2008), with stakeholder presence not necessarily translating to influence. For example, while a sector such as agriculture may be prioritized in a decision-process, large-scale agriculture producers have different needs and capacities than small-holder subsistence farmers. Due to this heterogeneity, differences in values, perspectives, and place-based characteristics are not necessarily represented due to varying capacities of participants. Acknowledgement of a broader array of human-environmental linkages may help ameliorate these shortcomings through identification of trade-offs across scales. However, the failure to actively engage with absent stakeholders leads to inequitable outcomes, as decisions made externally to affected peoples still impact their livelihoods and overall well-being (Berkes, 2009).

For underrepresented peoples who may have values and livelihoods closely tied to ecosystems, emphasis on a subset of values derived from specific contexts reduces the likelihood that their needs will be addressed. Reed (2008) notes that decision processes that include more diverse peoples and perspectives may still be dominated by traditionally-favored stakeholders due to power asymmetries and differences in capacity which should be addressed. However, broader inclusion of peoples a) affords opportunities for the articulation of broader objectives, b) can lead to ‘soft outcomes’ such as relationship building and trust necessary for continued engagement in such processes, and c) paves the way for collaborative solutions.

Values are shaped by factors such as culture, religion, and politics, producing a lens through which people interpret knowledge and evaluate management decisions, particularly when the values are closely tied to personal identity (Schall et al., 2018). While inclusion of previously underrepresented peoples in decision-making processes increases the likelihood that values and place-based needs are represented, it is important to understand how value systems, place, and identity inform how people make decisions. Identifying commonalities and facilitating compromises will likely require a) understanding the drivers shaping diverse perspectives, and b) innovative approaches for eliciting support for solutions (Schall et al., 2018). As such, the effect of decision outcomes on the well-being of peoples must be assessed in order to evaluate progress towards stewardship (e.g. Anderson, 2006). Therefore, the inclusivity of peoples, places, and their myriad perspectives and values are necessary for addressing the well-being of a broader array of peoples, assessing trade-offs, and producing solutions in a more equitable manner.

2.3.3 Diverse Knowledges

Addressing a broad range of environmental problems that manifest across scales and affect people in different ways requires integration of diverse knowledges. Long-term interactions within the human-environmental system help people make sense of their world.

While scientific knowledge is granted a level of legitimacy and credibility due to the systematic way in which it is produced (Raymond et al., 2010), knowledge is more generally produced through experiences, observations, and development of skills. For example, knowledge about the role of wetlands for species habitat and flood mitigation can be determined both scientifically and experientially (Fazey et al., 2005). However, what a person knows does not necessarily translate into a particular action. Rather, knowledge forms a foundation for values and preferences, informing what a person prioritizes (McLaren et al., 2008). How the role of the wetland for flood mitigation is valued compared to an activity that negatively impacts the wetland is therefore only partially driven by knowledge. Knowledge and values are closely tied, with values often producing conflicting views in how to interpret and mobilize knowledge.

Despite a broader recognition of harnessing diverse knowledges as a part of stakeholder participation processes, the ways in which knowledge is utilized is often influenced by what objectives are considered important (Stenmark, 2002). For example, data and indices are important elements for guiding policies and actions, often used to characterize trends in resource stocks and flows, hydrology, the economy, wealth, health, and proxies for human well-being (Kates and Parris, 2003). However, biases against other information sources may mask difficult to quantify relationships among people and the environment, thereby leading to their effective exclusion from decision-making. Understanding how value systems, place, and identity inform how people view and interpret different knowledges is thus an important step for identifying strategies to work towards shared understanding (Schall et al., 2018; Hitzhusen and Tucker, 2013).

The integration of non-scientific knowledge in decision-making is often concomitant with a consideration of a broader range of values representing more diverse system interlinkages. One prominent type of non-scientific knowledge comes from indigenous communities, who possess detailed knowledge about specific places over long temporal scales. This knowledge is adaptive, stemming from experiences, stories, and traditions

shared over generations (Turner et al., 2008). Indigenous ecological knowledge has been used to identify sites and species of local significance (e.g. Cummings and Read, 2016, cultural uses of fauna), inform management practices (e.g. Weiss et al., 2013, fisheries management), and link environmental and hydrologic indicators to indigenous practices (e.g. Jackson et al., 2015, environmental flows). However, indigenous knowledge is often underrepresented or absent from decision-making processes due to concerns around scientific rigor and legitimacy, its qualitative or tacit nature, and barriers related to sharing culturally-sensitive knowledge (Berkes, 2009; Jackson, 2008). These challenges lead to inherently inequitable decision-making processes where the concerns of indigenous peoples may be considered but their knowledge systems are not represented. On a related note, decoupling of knowledge systems from the contexts and values by which they are interpreted may a) result in ethical dilemmas in sharing and portraying culturally-sensitive knowledge, and b) fail to produce outcomes that are beneficial to knowledge holders.

Lack of action due to incomplete or missing scientific information further underscores the missed opportunities to engage with diverse knowledge types. Efforts on behalf of indigenous communities and scientists to mutually validate and complement indigenous knowledge and scientific records have illustrated not only the practical value of knowledge integration, but assessment of such approaches have been shown to empower communities and raise awareness for respectful knowledge inclusion (e.g. Gratani et al., 2011).

Non-indigenous experiential knowledge can similarly help identify needs, concerns and areas for new interventions (Bartels et al., 2013). However, Brook and McLachlan (2005) note that one-way validation of indigenous knowledge against scientific knowledge further marginalizes knowledge holders, underscoring the need for meaningful contributions by indigenous communities to ensure mutually-beneficial outcomes. The sharing of diverse knowledges a) stimulates new understandings of environmental systems (Fazey et al., 2006), and b) increases the likelihood that management decisions will be made with the consideration of local needs, values, and aspirations (Corburn, 2003; McLaren et al., 2008).

2.3.4 Governance and Institutions

The multiplicity of water users and uses demands systematic ground rules to meet societal needs and expectations. Governance is the “process of steering or guiding societies towards collective outcomes that are socially desirable” (Young, 2008). Governance systems are institutions comprised of rules, rights, processes, and social norms arranged to perform governance in the context of a place or issue. This includes rules for resource quality and use, legal frameworks dictating rights, and procedures by which decisions are made. Young (2008) characterizes governance through a set of considerations: a) fit between biophysical or social systems and governance arrangements, b) issues of scale or the appropriate level to address problems, c) interplay of institutions across scales and across domains, d) the impacts of institutions, and e) the effectiveness of institutions in addressing social goals such as transparency, fairness, and equity. These elements serve to disentangle governance, highlighting shortcomings in existing governance approaches. However, as governance constitutes efforts to organize and moderate human interactions with the environment, additional attention must be given to the representativeness of governance systems in regards to how peoples, values, knowledges, and relationships with the environment are understood and prioritized on an ongoing basis.

Challenges arise when governance systems – formal and informal systems consisting of entities such as governments, communities, and resource users – are improperly specified for a given context. Historical issues of fit and scale constitute a barrier to considering broader system interlinkages. Examples include a) mismatches between administrative and hydrologic boundaries and b) translation of governance arrangements to other scales. Woodhouse and Muller (2017) note that while river basin scale planning has been promoted to ameliorate these shortcomings, the application of knowledge about governance arrangements without consideration of local contexts requires attention in current approaches. For example, efforts to implement public participation processes have resulted in mixed outcomes in part due to lack of local capacity, and political and historical tensions

(Reed, 2008). Relatedly, issues of interplay arise from interactions across scales resulting in concurrent governance regimes; conflicting fisheries management practices between governments and indigenous communities are a key example (e.g. Dale and Natcher, 2015).

To address these deficiencies, multi-level arrangements have been promoted to coordinate governance across scales, problems, and peoples (Young, 2008; Ostrom, 2010; Armitage and de Loë, 2012). Coordination can range from communication and consultation across jurisdictions, to partnerships with non-State actors. Examples of such co-management arrangements include: partnerships between Federal and Tribal governments to manage a range of resources (e.g. Cronin and Ostergren, 2007; Hill et al., 2012), fishers and resource managers (Gutiérrez et al., 2011, e.g.), and land-use management through partnerships with local governments, citizens, and non-profit entities (e.g. Olsson et al., 2004). Such arrangements may be facilitated through NGOs, universities, and user groups engaged in boundary work including documentation of knowledges through tools and visual media (Clark et al., 2016), building participatory capacity, and fostering trust between partners (e.g. Kirchhoff et al., 2013). While such partnerships offer opportunities for inclusion, the specification of governance systems must be representative of SES dynamics of peoples, their values and needs, and knowledge systems.

Identifying the set of policies, legal, legislative, and financial elements that set the framework for how governance is performed on an ongoing basis is critical for understanding opportunities and addressing weaknesses. However, factors such as jurisdictional conflicts, power imbalances, and local capacity may undermine efforts to reflect broader human-environmental interlinkages and facilitate inclusion. For example, policies such as Australia's National Water Initiative (2004) and U.S. realignment of groundwater and land rights (Womble et al., 2018) provide opportunities for integration of indigenous knowledge and values. However, regulatory frameworks delineating the use of scientific information in government policy-making pose challenges (Wagner et al., 2018). Governance arrangements that are attentive to broader interlinkages may be more responsive to multiple objectives.

For example, environmental flow rules such as the State of Maine *Chapter 587: In-stream Flows and Lake and Pond Water Levels*(2007) are responsive to human-environmental connections, offer an innovative approach for policy and rule-making, and are well-poised to lead to workable solutions for a broad range of peoples and perspectives.

Governance arrangements are essentially an imposed organization of society's understanding and prioritization of human-environmental interlinkages, peoples, place, values, and knowledges. While Young (2008) carefully delineates a range of important governance characteristics, stewardship calls for an addition: the representativeness of governance structures. While the effectiveness of institutions in achieving societal goals is an important consideration, there must be a reflexive relationship with the specification and design of governance systems and representativeness to enable equitable outcomes. To this end, governance systems must be structured to promote the inclusion of diverse peoples, knowledges, and perspectives. It is noted that incremental or transformational changes in some or all of the above characteristics of governance are necessary to design arrangements that are enablers of equitable outcomes.

2.3.5 Co-produced Solutions

The ways in which peoples are able to participate in management decisions determines the likelihood of producing more equitable solutions. While broadened participation and forms of multi-level governance provide opportunities for inclusion and diverse knowledge integration, presence alone does not necessarily produce desired outcomes. Processes must be collaborative rather than driven by the elicitation of knowledge from local peoples and communities by researchers or government organizations. In one example, Woodward (2010) details the collaborative production of indigenous seasonal calendars between community members and researchers, linking hydrologic variables to sites and species of cultural and economic significance. Supported by an acknowledgement and appreciation for diverse knowledges, such collaborations lead to the production of relevant information that

supports community needs and values while having linkages with scientific information that may enable smoother integration into decision processes. The calendars serve the dual purpose of facilitating potential inclusion of indigenous knowledge in decision-making processes and use as educational tools within and outside of indigenous communities.

Examples of practices spanning a range of researchers, communities, and resource practitioners include: a) photo-voice methodology for sharing cultural practices and identifying important sites for indigenous hunting and fishing (e.g. Maclean and Cullen, 2009; Jackson et al., 2015), b) participatory modeling for indigenous water planning (Hoverman and Ayre, 2012) and community land management in northern England (Dougill et al., 2006), c) integration of scientific information and planning time-scales for resources managers concerning fire (Corringham et al., 2008), streamflow (Kim and Jain, 2010), and other climate-sensitive decisions (Lackstrom et al., 2014), d) identifying hazards such as landslide risk in California (Linnerooth-Bayer et al., 2016), and e) community-based monitoring in northern Canada (Berkes et al., 2007). Rathwell and Armitage (2016) offer an overview of collaborative learning approaches that are applicable to a wide range of participants. These collaborative activities not only result in the two-way transfer of local and scientific knowledge tied to a broader range of views and perspectives, but they are used to build trust, ensure representation, aid communication and translation of cultural concepts, and enable the tracking of change over time (Moller et al., 2004; Dilling and Lemos, 2011; Rathwell et al., 2015).

Co-production approaches are inherently more inclusive than one-way elicitation of knowledge and views by experts and decision-makers as they enable knowledge holders to play a more active role in how their knowledge is represented and interpreted. Particularly for peoples who have been underrepresented in decision-making processes, the tools produced by collaborative approaches can be used to bridge knowledge gaps in diverse multi-level governance systems. Such approaches and tools facilitate knowledge exchange and increase the opportunities for understanding and identifying commonalities needed in

inclusive processes. However, the nature of these partnerships is dependent on context and many are built through long-term commitment and trust. For example, Sillitoe (1998) argues that indigenous knowledge should not be separated from socio-environmental context and identifies common barriers to its integration. This includes the fact that skill-based knowledge is often not articulated and communicated within decision-making processes. He also notes barriers that are applicable to collaborative processes more generally, including mismatches between management time-frames and the time needed to build relationships, and lack of commitment to consensus in decision processes. The examples provided above illustrate that collaborative practices among peoples and institutions can help to ameliorate some of these issues a) increasing the capacity of previously underrepresented people to actively participate in crafting solutions, b) creating opportunities for the development of new ways of learning and knowing necessary for addressing changing conditions and emerging challenges, and c) increasing the likelihood that solutions are responsive to a more diverse view of the human-environment system.

2.3.6 Adaptive Risk Management

Dynamic feedbacks are inherent to the human-environmental system due to its interlinked nature. Social and climate-induced changes propagate across landscapes over time. As such, systems re-equilibrate, yet may become more vulnerable to experiencing negative impacts with implications for both human and ecological well-being. As with governance, responses to the effects of negative impacts reflect how human-environmental interlinkages and related knowledges are understood and prioritized. Risk is constituted by the combination of likelihood and consequence of an event. Broadening attention to system interlinkages and the diversity of ways in which people experience and respond to risk enables more equitable responses. For example, reduction in precipitation increases drought risk, but will result in materially different risks to people depending on context. Source of livelihood, possession of water rights, access to alternative water sources, financial capacity

and other socioeconomic factors will influence the severity and type of impacts a person experiences, underscoring that understandings of risk must include the interacting environmental and social factors that increase or reduce vulnerability. As such, how risk is managed has implications for equity. Strategies and tools for anticipating and responding to risks may be ineffective without consideration of local needs and barriers.

Communicating risk ranges from short-term warnings regarding events to long-term outlooks such as seasonal or multi-year drought events. For example, early warning systems (EWS) are widely used to disseminate information about imminent hazards and are critical to saving lives and reducing impacts by prompting people to prepare for and respond to threats. However, non-environmental factors such as education level, financial resources, age, physical ability, and social discrimination affect the capacity of individual to access information and effectively respond, with vulnerable populations disproportionately affected (UN Environment, 2015). The use of tools over longer time horizons helps people anticipate and minimize risk on an ongoing basis. For example, seasonal climate forecasts for farmers can be used to make decisions regarding planting times and water storage and use. However, lack of access to information, technology-use gaps, and lack of transferability of tools to other contexts impact the level of benefit (Fothergill and Peek, 2004; Eriksen and O'Brien, 2007; Anguelovski et al., 2016). Understanding the interacting social and environmental elements that produce and exacerbate risk is therefore necessary to respond to inequities in how benefits from interventions are disseminated.

Strategies such as collaborative development of indicators to track systems towards and away from risk thresholds are grounded in local knowledge and provide peoples with tools to characterize risk in ways that may otherwise go unaddressed (Reed et al., 2008; Alessa et al., 2016). Conversely, extraction of local knowledge and information about needs may fail to detect vulnerabilities or result in tools that are not usable by communities, falling short of mitigating risks (Klenk et al., 2015). As such, risk reduction interventions that integrate a broader conception of human-environmental interactions and inclusion of

peoples and knowledges are likely to be more well-poised to respond to the myriad factors that contribute to risk leading to more appropriately tailored interventions (Pfaff et al., 1999; Lemos and Dilling, 2007; Furman et al., 2014).

Changing baselines and external perturbations present challenges to systems. Extreme climate-driven events, landscape alteration, demographic and social changes, migration, trade and economic changes, and political events cause reverberations and feedbacks within the SES. Risk-based approaches as noted above have historically focused on quantifying the risk of single events based on historical conditions. As a result, existing infrastructure, management plans, and adaptation strategies are ill-equipped to address the risk of multiple interlinked events such as sequential precipitation events (Schröter et al., 2015) or simultaneous storm surge and precipitation events (Wahl et al., 2015; Zscheischler et al., 2018). Factors that extend beyond hydrologic boundaries pose additional challenges. Inter-basin water transfers (Zeitoun et al., 2016), and the impact of virtual water trade in and out of watersheds (Mekonnen and Hoekstra, 2011; Marston et al., 2015) may influence local supply and lead to increased risk for peoples and the environment.

How governance systems anticipate, respond, and recover from such changes has implications for peoples and scales. Risks may manifest over longer periods of time in response to governance and changing baselines including changes stemming from efforts to mitigate impacts. For example, migration in response to resource depletion or a disaster may lead to new vulnerabilities as peoples lack the local knowledge necessary to anticipate and respond to risks in a new location, exacerbating existing inequities or creating new ones (Birkmann et al., 2013). Emerging needs and populations, new knowledge bases, and changing values and priorities around relationships with the environment that are not attended to by governance systems and associated adaptive strategies can result in unexpected consequences and challenges.

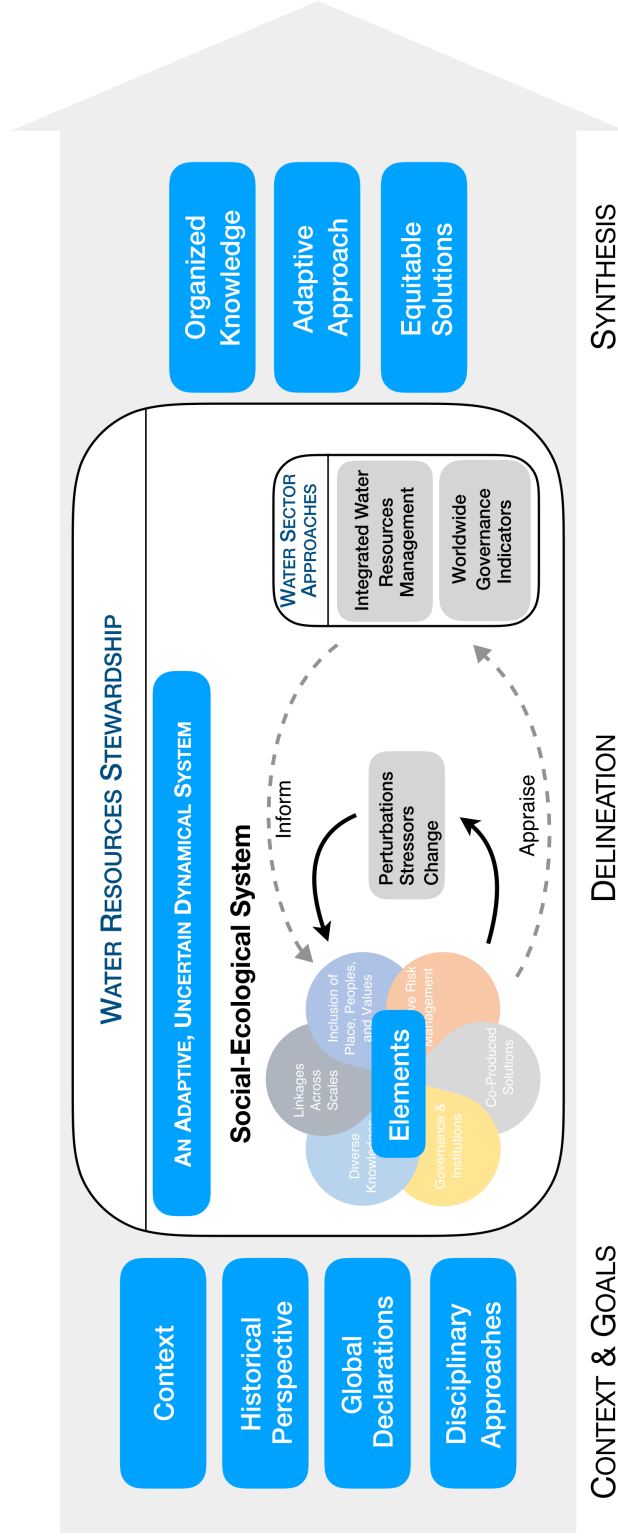


Figure 2.2: Water Resources Stewardship within a systems context.

2.3.6.1 Systems-level View of Stewardship

Stewardship enables a broader delineation of the SES, represented as a responsive and adaptive system. While other approaches have focused on the need for adaptive governance and institutions to contend with changing baselines and perturbation, stewardship gives equal weight to elements of the SES that are subsumed by these approaches: interlinkages between people and the environment, inclusion, and diverse knowledges. In the absence of direct attention to these elements, efforts to adjust governance to contend with deficiencies such as mismanagement, environmental degradation, and inequities in well-being fall short of aspirational goals. In a complex and dynamic system, adjustments to governance are fraught with uncertainties and the lack of reflexive relationships between approaches and representativeness may render institutions ineffective. As such, stewardship offers opportunities for iterative reappraisal, offering opportunities to learn from shortcomings and adapt to changes on an ongoing basis promoting trajectories towards sustainable and equitable futures. This work acknowledges that there are limitations to which these elements can be addressed in over-allocated or highly regulated systems, locations with high economic dependency on single-resources, or places with weak governance. However, integration of stewardship elements to the extent possible promotes movement to more sustainable and equitable systems. As a widely promoted and applied framework for water resources management, IWRM and associated development indicators offers a unique vantage point to inform stewardship elements while also offering a synthesis of challenges and opportunities of current approaches (Figure 2.2).

2.4 IWRM: From Concept to Practice

IWRM is often defined as “a process which promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems”(Global Water Partnership, 2000); calling for public

Table 2.1: IWRM Thematic Keywords

Economy	Society	Environment	Other
Economic Benefits	Social Benefits	Ecosystem Health	Sustainability ¹
Economic Sustainability	Under-represented Groups ²	Environmental Sustainability	Monitoring
Profits	Human Well-being	Water Quality	Adaptation
Efficiency	Equity	Water Quantity	Resilience
Economic Good	Social Good	Stewardship	...

¹ General Use

² Women and Indigenous Peoples

participation, river basin planning, and coordinated multi-level governance. IWRM has been implemented across the globe at various scales with organizations such as the Global Water Partnership (GWP), UN, World Bank, and other development organizations serving roles in IWRM discourse, policy development, and implementation support (Allouche, 2016). The GWP has been particularly influential, producing a range of guidance documents on topics such as equity, capacity building, and governance, as well as an ‘IWRM Toolbox’ outlining a range of approaches for implementation. However, the breadth of foci coupled with an absence of a clear conceptual framework has led to challenges in bringing concept to practice, with evidence of fragmented implementation (Medema et al., 2008). Giordano and Shah (2014) note that surveys on IWRM implementation tend to focus on the adoption of IWRM language rather than the outcomes of implementation, suggesting that the status-quo may be maintained in practice, despite the appearance of interventions. Therefore, case studies serve as a vantage point for understanding how IWRM is construed and implemented on global and regional scales and for appraisal through a stewardship frame (Figure 2.2).

2.4.1 IWRM Case Methodology

A set of 30 case studies describing IWRM implementation and sharing a common definition (Figure 2.3) were selected from peer-reviewed journals and books to: a) identify the occurrence frequency of key themes deductively selected from IWRM literature (Table 2.1), and b) reappraise case studies through a stewardship lens: organizing

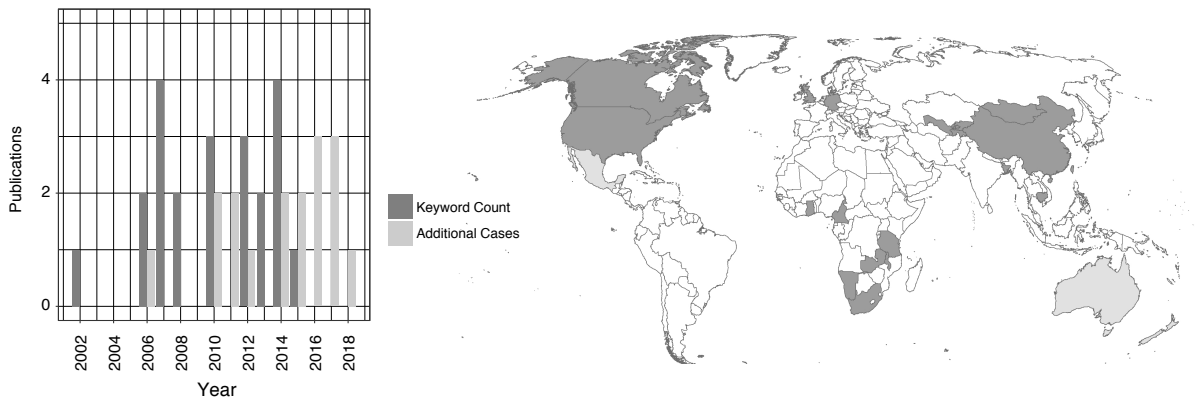


Figure 2.3: IWRM case study timeline. Note that some publications include more than one case study. Cases not meeting the keyword count criteria but used for IWRM appraisal are marked in light gray.

knowledge around problem issues, inclusion of peoples and values, institutions, and monitoring (Table 2.2). Case studies detailing a specific component of IWRM implementation, such as public participation processes, were used to further contextualize thematic keyword counts. Additional methodology can be found in Online Resource 1. Three key themes were used to assess case studies: 1) balance among human and environmental objectives, 2) public participation, and 3) monitoring and adaptation. Each study has its own scale and foci according to the idiosyncrasies of each context and the authors' own interests. This limits the level to which the case studies can be appraised through a stewardship lens. Nevertheless, they provide insights into existing gaps and future opportunities to address shortcomings.

2.4.2 IWRM Themes Across Regions

Globally, environmental keywords comprise a higher frequency of keywords than those in the social and economic themes (Figure 2.4). Regionally, environmental keywords dominate North American (47%) and European (48%) cases while African cases show a similar frequency across environmental, social, and economic themes. Asian case studies show higher incidence of economic and social categories. Despite these regional differences,

terms representing IWRM outcomes such as social benefits, equity, and environmental health, occur consistently across regions. While this indicates commonalities in how IWRM is framed, keywords associated with these outcomes are notably limited by comparison. For example, while equity dominates the social theme, there are few mentions of human well-being and minority populations. Higher incidence of ‘water quality’ over ‘quantity’ are also notable due to the emphasis of IWRM on balancing water needs given critical role of water flow in sustaining healthy ecosystems (Poff et al., 1997; Arthington, 2012). It is also notable that ‘sustainability’ is often mentioned without additional context or a definition (10%), suggesting a lack of specificity. While a high frequency of keywords associated with IWRM outcomes is expected, the lack of terms associated with those outcomes suggests narrow framings of human and environmental well-being and equity. Although not exhaustive, these keywords indicate a level of similarity in how IWRM is framed across the case studies. In depth reappraisal of these case studies supported by additional IWRM literature offers insights into how themes are featured and align with a stewardship perspective.

2.4.3 Theme 1: Balancing Human and Environmental Objectives

IWRM places water as a central resource but emphasizes integration across land and related sectors providing the basis for recognizing diverse interlinkages. Cases reflect commonalities in their description of broader environmental and social concerns such as precipitation variability, population changes, and competition among different uses of water (Table 2.2). Despite the IWRM emphasis on integration, many cases tend to frame IWRM interventions narrowly, limiting insights regarding if and how there has been a shift towards a broader suite of objectives. For example, inadequate infrastructure coupled with a history of government prioritization of large irrigation and hydropower projects in Tanzania has resulted in inadequate infrastructure to support drinking water and sanitation systems (Maganga et al., 2002). While increased efficiency and yields have

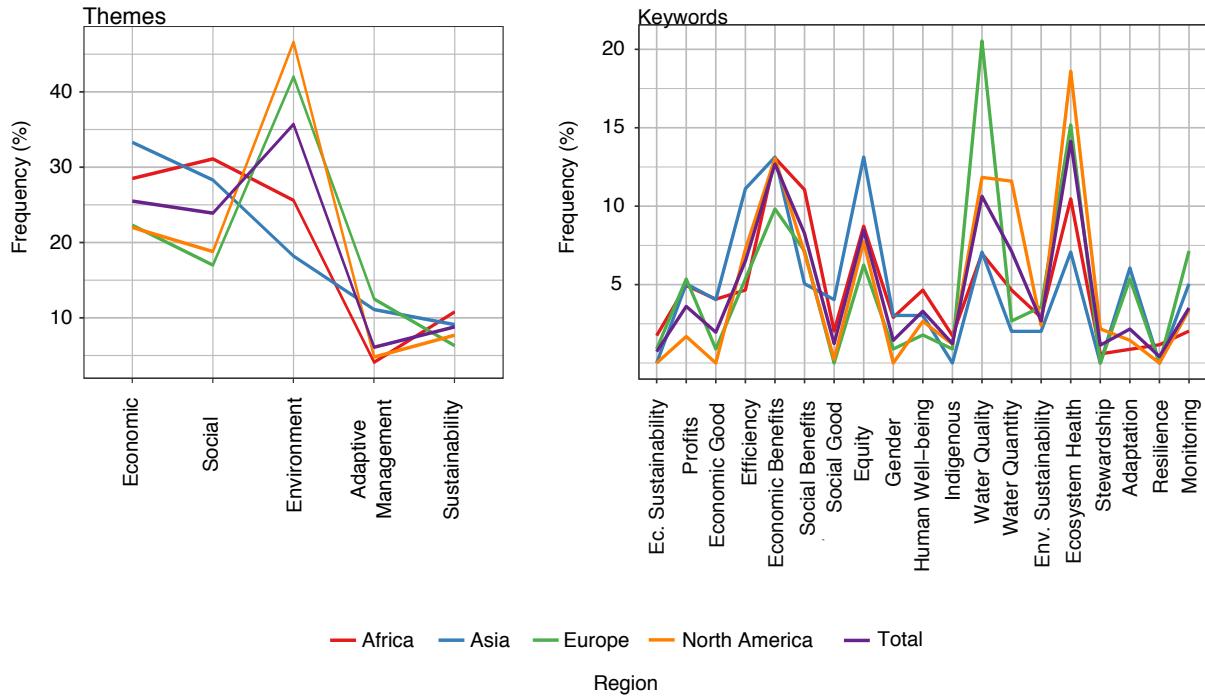


Figure 2.4: Frequency of themes and keywords in select IWRM studies by region. Frequency is calculated as the proportion of the total number of keywords mentioned for all studies in each region.

accompanied investment in irrigation in Africa (van Koppen et al., 2016) and Asia (Dukhovny et al., 2013), conflict among uses remains a concern. Broader environmental objectives on local levels to support subsistence and customary uses are alluded to (Maganga et al., 2002; Kluge et al., 2008; Benito et al., 2010), but appear to lack attention in government-driven processes. Similarly, a few cases note allocation of water for fishing and general aquatic health (Ako et al., 2010; Dukhovny et al., 2013), but offer few insights regarding IWRM as vehicle for environmental conservation. For example, while the EU Water Framework Directive (WFD) calls for development of a suite of ecological indicators to track ecosystem health, lack of progress suggests environmental considerations are lagging behind other priorities (European Commission, 2015). Also notable across case studies is a lack of consideration of the interlinked nature of the hydrologic system, with few studies mentioning groundwater resources. While Australia has made strides towards conjunctive management of water resources, efforts have been limited by the complex

overlap of management units coupled with the historical separation of institutions (e.g. Ross, 2018). Although IWRM sets the stage for the acknowledgement of interlinked systems and trade-offs among multiple objectives, integration in practice appears limited to the water sector and historical patterns of use.

2.4.4 Theme 2: Public Participation and Inclusion

IWRM implementation is an ongoing activity with case studies illustrating different stages of changes in governance arrangements to promote integration, basin-level planning, and public participation. All case studies illustrate a level of decentralized decision-making through formation of local-level organizations and limited devolution of responsibilities once held by central government. However, barriers to multi-level coordinated governance are also evident despite a commitment to stakeholder participation and integration across hydrologic and administrative boundaries in legislation. IWRM efforts to overcome historical shortcomings and cited barriers in practice include:

- a) Reorganization of institutions to work across sectors coupled with a lack of cooperation and information sharing. **Key examples:** IWRM focus on irrigation and hydropower projects in Asia with lack of integration with broader interests (Rouillard et al., 2014; Dukhovny et al., 2013), and power-sharing issues in the Netherlands (Heijden and Heuvelhof, 2012).
- b) Establishment of basin-scale organizations for locally-informed decision-making coupled with lack of funding, expertise, or legal authority to develop and implement plans. **Key example:** South Africa Catchment Management Agencies (CMAs) designed to enable basin-level planning with input from local stakeholders have been limited by financial and data resources, personnel, expertise, and ability to operate on short timelines set by donor agencies leading to lack of progress (Ballweber, 2006; Funke et al., 2007; Meissner et al., 2016).

- c) Stakeholder participation processes without acknowledgement of representativeness. **Key examples:** South Africa CMA decision processes show limited access of vulnerable peoples to due to poverty, education level, and social disparities. In Tanzania, emphasis on cost-recovery by government investment in irrigation inadvertently prioritized large-scale users and overlooked subsistence and customary needs (van Koppen et al., 2016).
- d) Development of management plans coupled with temporary funding in government budgets or by donor agencies that limit capacity for long-term management programs. **Key examples:** California's voluntary state IWRM program provided funding for plan development through grants but not for implementation (Lubell and Lippert, 2011). Similarly, Canadian efforts have lacked consistent funding mechanisms (Scott et al., 2017; Leclerc and Grégoire, 2017).

Some studies also note that top-down governance objectives further exacerbate these issues by overriding local interests. For example, while the WFD requires stakeholder participation, it does not specify actors or the type of engagement along a spectrum of consultation to collaboration. Benson et al. (2014) found that government objectives dominated the final outcomes of basin planning documents in England, despite public participation efforts. This may be partly due to compliance with standards and reporting set by the EU. A lack of meaningful inclusion may lead to public mistrust and disengagement in future processes. Historical tensions between governments and traditional systems contribute to distrust (e.g. Dolan and Middleton, 2015; Yu et al., 2014), while entrenchment of historic top-down structures may limit involvement as exemplified by hydropower and irrigation planning in Central Asia (Dukhovny et al., 2013; GWP, 2014; Abdullaev and Rakhmatullaev, 2014).

However, opportunities for success are apparent as well. For example, Dolan and Middleton (2015) found that government and tribal co-management in California were

more successful where pre-existing relationships had been cultivated and land and water rights were maintained by tribes. In other cases, local efforts may be initiated due to government inaction, such as in Mexico where local peoples have worked to address environmental degradation and user conflict due to government investment in large-scale infrastructure and a failure to follow IWRM principles (Ochoa-García and Rist, 2018). While IWRM is characterized by a shift towards broadening participation, cases illustrate that absence of representation of local peoples and their values, and lack of local capacity to support local ownership of decision-making undermines efforts.

Table 2.2: Regional Appraisal of IWRM Case Studies

	Africa	Asia	Europe	North America	Oceania
Countries	Cameroon, Ghana, Malawi, Namibia, South Africa, Tanzania, Zambia	Bangladesh, Cambodia, China, Kyrgyzstan, Mongolia, Tajikistan, Uzbekistan	England, Germany, Netherlands	Canada, Mexico, United States	Australia, New Zealand
Key Issues	Sectoral competition, access to drinking water and sanitation, food security, precipitation variability, poverty and health, and transboundary coordination		Sectoral competition and over-allocation, climate change impacts, water quality and supply reliability, ecosystem health, flood and drought hazards, and transboundary coordination		
Actors	Typical stakeholders include formal government, non-governmental organizations, donor organizations (Africa and Asia), water managers, agricultural and industrial interests, and environmental organizations. Level of involvement of the general public, tribal and community leaders varies by context.				
Enabling Environment	Adopted in national level legislation. Recurring emphasis on pursuing cost recovery. Establishment and reorganization of water rights have created barriers for traditional systems (e.g. Tanzania). Largely supported by donor organizations.	Adopted in national level legislation. Strong focus on investment in water storage and delivery infrastructure for irrigation. Support from foreign donor organizations.	IWRM principles adopted by the EU Water Framework Directive (WFD). Requires all EU countries to delineate river basins and authorities and develop basin management plans. Requirements for monitoring and reporting for environmental objectives.	Adopted nationally in Mexico. In US, some state-level voluntary initiatives (e.g. California) and adoption of principles in federal agencies. Provincial adoption in Canada with limited funds from federal government.	IWRM principles in national level legislation. Additional institutions set at State (Australia) and Regional (NZ) levels. National government provides some monetary support for implementation. Water rights allocated to indigenous and customary uses.
Institutions	Rearrangement of existing water-related institutions and establishment of basin-level organizations. Responsibilities are devolved to local level institutions, but central authority is maintained. Public participation is supported but due to capacity issues is dominated by existing stakeholders.	Rearrangement of existing water-related institutions and establishment of basin-level organizations. Coordinating role by central government. Participation opportunities to develop basin-level plans in some countries, but priority given to economically-valued stakeholders.	Requirement of public participation for developing basin-level plans. Reorganization of institutions to align with basin-level planning (e.g. Netherlands). Movement towards integration of surface and groundwater planning.	Public participation highly promoted and required in some cases (e.g. California). Complex arrangements within federated systems due to overlapping jurisdictions. Arrangements may consist of formal agreements and voluntary partnerships.	Requirement of public participation for developing plans, specifically indigenous interests. Regional governments arranged by basin in New Zealand. Efforts for multi-level coordination with some funding support from higher levels.
	:	:	:	:	:

Table 2.2: Regional Appraisal of IWRM Case Studies (Continued)

	Africa	Asia	Europe	North America	Oceania
Management Instruments	Monitoring is largely limited to surface water quality and quantity. Limited discussion of water markets for cost recovery.	Monitoring is largely limited to surface water quality and quantity. Development of hydrologic and ecological modeling, but limited data. Permitting programs often lack enforcement.	Strong emphasis on monitoring to meet WFD benchmarks. In practice, lack of progress towards ecological monitoring and stronger progress towards surface water goals. WFD goal of introducing pricing mechanisms for water use.	Recognition of monitoring needs, but often lack of funding to support long-term monitoring on local levels. Local-level initiatives for monitoring but lack of uptake by managers.	Diversity in monitoring approaches by lower-level governments. Establishment of water markets in Australia to allocate water from low value to high value uses. Discussion of citizen science and indigenous knowledge utilization.
Challenges	Funding sources for specific projects prioritized by government or donors. Lack of capacity for local level governance despite participate opportunities. Monitoring projects are limited by funding, expertise, and personnel.	Lack of local trust in government (e.g. China) and issues with corruption undermine efforts for coordinated management. Funding and local level capacity issues limit monitoring efforts and basin-level plan development. Limited data sharing	Mismatch between local and national goals, with participation often limited to consultation. Lack of progress towards monitoring for ecological indicators. Opportunities for transboundary coordination due to common WFD framework.	Coordination challenges among administrative boundaries, such as integrating projects with existing water-related plans. Limited or sporadic funding for long-term monitoring and plan implementation. Lack of attention to facilitating Tribal interests beyond requirements of existing institutions.	Mixed results by State (Aus) and Regional council (NZ). Lack of consistent funding. Efforts to include indigenous peoples successful in some cases, but evidence of narrow framing of water needs and lack of uptake of indigenous knowledge.
Examples	Maganga et al. (2002); Ballweber (2006); Agyenim and Gupta (2012); Meissner et al. (2016); van Koppen et al. (2016)	Horlemann and Dombrowsky (2012); Dukhovny et al. (2013); Rouillard et al. (2014); Yu et al. (2014); Irvine et al. (2010)	Heijden and Heuvelhof (2012); Richter et al. (2013); Watson (2014); Benson et al. (2014)	Cervoni et al. (2008); Shively and Mueller (2010); Dolan and Middleton (2015); Melnychuk et al. (2017); Ochoa-García and Rist (2018)	Davis and Threlfall (2006); McNeill (2016); Baldwin and Hamstead (2015); Mitchell et al. (2015)

2.4.5 Theme 3: Monitoring and Appraising Outcomes

Monitoring and evaluating plan development, implementation, and outcomes is a central piece of the IWRM framework. Delineating system characteristics and tracking changes is essential to identifying features that move the system towards and away from desired outcomes. However, critics point to a lack of documented success (Biswas, 2008; Giordano and Shah, 2014) and case studies suggest that there is a lack of coordinated monitoring efforts, in part due to financial constraints. For example, Agyenim and Gupta (2011) cites lack of funding and personnel, accessibility to remote locations, and telecommunication issues as barriers to developing a monitoring service in Ghana. Many case studies note international donor organizations as funding sources, with the limited funding time frames coupled with government financial capacity and willingness to engage in long-term monitoring projects contributing to a lack of progress. Inability of

impoverished populations to meet user fees further exacerbate this issue, with fee structure changes put forth as a way to finance ongoing implementation and monitoring.

Conversely, well-funded initiatives in the EU show presence of data monitoring and reporting in line with EU criteria (Forrester et al., 2015). However, recent synthesis reports show that member countries are behind in using biophysical indicators required by the WFD (European Commission, 2012). In the US and Canada, cases suggest priority is given to plan development and implementation, with less emphasis towards funding monitoring programs (Cuvelier and Greenfield, 2017). Volunteerism and citizen monitoring have been suggested as ways to engage the public, overcome funding limitation, and serve as education opportunities. However, uncertainty as how to integrate citizen science into decision-making poses a barrier to uptake (Forrester et al., 2015). These barriers limit insights into IWRM's progress in addressing a range of cited priority issues such as water quality and quantity, sectoral competition for resources, agricultural yields, and precipitation variability. Progress towards addressing less prioritized objectives and needs is even more uncertain. In New Zealand, federal funding criteria for IWRM projects does not allow for cultural and community monitoring, offering few opportunities for projects to address indigenous initiatives through those funding pathways (McNeill, 2016). Overall, while monitoring is a clear element of the IWRM approach, in practice it appears to receive less attention than plan development and implementation.

2.5 Appraisal of IWRM from a Stewardship Perspective

A useful next step is the examination of the manner in which the three IWRM themes encapsulate the six elements of Water Resources Stewardship (Figure 2.5). The extent to which each theme features elements of stewardship is categorized by strong, moderate, or weak. Stewardship elements that are not directly applicable to the given theme are left blank. Theme 1 moderately features an acknowledgement of interlinkages across scales. Case studies emphasize a need to integrate across sectors, but illustrate a tendency to

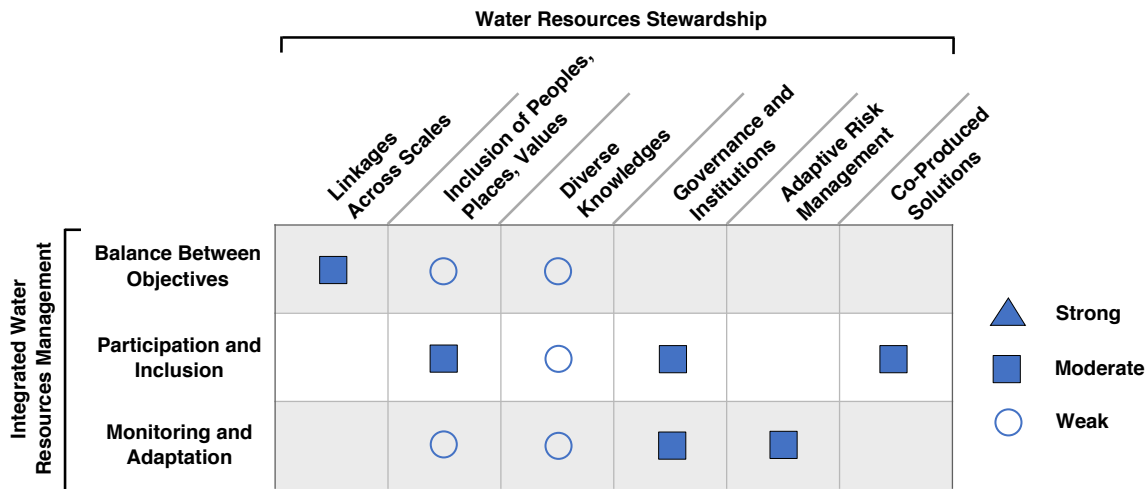


Figure 2.5: Appraisal of IWRM from a Water Resources Stewardship Lens

prioritize agriculture and drinking water, with lower emphasis on cultural, subsistence, and ecological water needs. Furthermore, few case studies (e.g. Ross, 2018) mention or consider the inherent dependencies among groundwater and surface water sources. In relation to these priorities, a broader inclusion of peoples, values, and knowledges is needed. A strong emphasis on interlinkages across scales would entail not only attention to resources and individual users, but also careful attention to interactions across scales. Similarly, diverse knowledges are a critical prerequisite for a fuller explication of cross-scale interlinkages that may pose challenges, but also afford opportunities based on local and experiential knowledges.

Theme 2 shows a stronger emphasis on inclusion through a commitment to local-level and stakeholder participation processes. These provide an opportunity for broader inclusion of voices, with the South African CMAs offering a prominent example of a new governance institution for local-level engagement. However, as noted above, the quality of these processes ranges across cases, with shortcomings evident. For example, cases in Africa and Asia noted factors such as poverty, education, and social tensions as barriers for broader inclusion. Prioritization of large-scale and economically valued users dominated these processes. In other cases, government objectives may override stakeholder input (e.g.

Benson et al., 2014). While needing further attention, the attempt to create venues for more collaborative water planning is noted. The level to which non-scientific knowledge features in these processes is unclear, prompting a weak designation for diverse knowledges.

Finally, case studies show moderate gains around Theme 3 regarding institutions and measures for monitoring, and efforts towards adaptive planning. As in Themes 1 and 2, limitations in monitoring coincide with shortcomings in other stewardship elements such as knowledges and inclusion. Lack of representation in decision-making processes coupled with narrow framings of human-environmental interlinkages largely precludes monitoring programs from tracking changes of importance to absent stakeholders. By broadening representation and drawing explicit attention to diversity in human-environmental linkages, knowledges, values, and the institutional arrangements that enable or disable representation, stewardship increases the likelihood of addressing these issues. Lack of monitoring not only limits insights into the drivers of IWRM successes and shortcomings, but it further limits the ability to detect change and adjust management strategies and governance arrangements to promote progress towards sets of objectives, undermining efforts to include adaptive approaches. Therefore, ‘inclusion of peoples, places, values’ and ‘diverse knowledges’ require more attention.

While IWRM has played a critical role in supporting responsible management of water resources and has promoted a shift towards broader public participation and consideration of hydrologic and administrative scale mismatches, manifold barriers to addressing challenges are evident when viewed through a stewardship lens. Across themes, no elements of stewardship are fully addressed, informing the framework. While moderate gains are noted across various stewardship elements, gaps exist particularly regarding inclusion and diverse knowledges. Next, the use of national-level indicators on the global scale to characterize and track change in the water sector is considered.

2.6 National-level Indicators on the Global Scale to Inform Stewardship

Indicators are tools to represent and organize knowledge, and are often used to set targets, and track progress towards development goals. National-level indicators on the global scale are used by organizations such as the UN and World Bank to characterize the state of the system and identify linkages among issues. Stewardship draws attention to the importance of interlinkages across scales, as conditions and management decisions outside the scale of planning can produce exogenous pressures. Indicators offer a way to identify potential externalities that may influence the state of economies, water sectors such as agriculture and industry, and exacerbate existing challenges. Here, the World Governance Indicators [WGI; (Kaufmann et al., 2010)] are considered as a metric for characterizing the state of governance across countries and green and blue virtual water import and export activity as an example case of exogenous pressures.

2.6.1 Selected National-Level Indicators

National-level virtual water data (Hoekstra and Mekonnen, 2016) describes the volume of water exported and imported through food and other commodities. This includes blue water (surface and groundwater) and green water (precipitation held in soil water and fluxes within plants), with both constituting important input to economic enterprises. As such, economic activities may be sensitive to changes in international trade and social and environmental conditions in other places (Orlowsky et al., 2014; Hoekstra and Mekonnen, 2016). To characterize the relative balance between import and export water volumes, the percent difference between virtual water imports and exports for blue and green water were determined (Figure A.1). Higher percentages of blue exports relative to imports are found in Australia, southeast Asia, and South America compared to imports, with higher percentages of blue imports in Europe and much of Africa. Higher percentages of green water exports through agricultural products are found in Africa, South America, and North America, while Europe, the Middle East, and parts of Asia import higher percentages.

The WGI (Kaufmann et al., 2010) offer a global database of national-level indicators comprising six characteristics of governance, consistent with elements noted in global declarations and IWRM literature. The primarily perception-based indicators are aggregates of national, regional, and household level datasets, normalized from weak (-2.5) to strong (2.5) performance compared to other countries evaluated. They are defined as:

1. Voice and Accountability (VA): perception of citizen ability to participate in government selection, as well as freedom of expression and a free press.
2. Political Stability / Non-Violence (PS): perception of the instability of the government, and the likelihood of politically-motivated violence such as terrorism.
3. Government Effectiveness (GE): perception of the quality of public services, how independent civil services are from political pressures, the quality of policy making and implementation, and the credibility of commitment to policies that are instituted.
4. Regulatory Quality (RQ): perception that the government is able to formulate and implement policies and regulations to promote private sector development.
5. Rule of Law (RL): perception of how well others follow the rules of society and how well government enforces rules and regulations, the quality of property rights, contract enforcement, the police, judiciary, and likelihood of experiencing crime or violence.
6. Control of Corruption (CC): perception that people use public power for personal gain and the influence of private interests on the State.

The 2016 WGI were aggregated into a leading statistical pattern accounting for 83.7% of individual indicator variability (Figure 2.6a, Figure A.2). The first leading pattern shows moderate correlation among all indicators, with a higher score indicating stronger governance due to high scores in all indicators. The first pattern shows highest governance scores for the US, Canada, Australia, western Europe, and parts of Southern Africa, with

lower scores in the Middle East, Africa, Central America, and Asia. A second leading pattern explaining 7.5% of indicator variance identifying countries with diverging VA and PS scores from the other indicators and regionally representative governance patterns can be found in Appendix A.

While IWRM emphasizes good governance, IWRM framings do not specify governance components to be identified and tracked. IWRM survey data from a recent SDG Target 6.5.1 progress report (UN Environment, 2018) shows a positive correlation ($r = 0.60$) with the leading governance pattern. This suggests that countries characterized by higher governance show higher levels of implementation. However, these surveys are largely concerned with the adoption of new policies and institutions, and not the effectiveness of IWRM at addressing specific problems (Petit, 2016; UN Environment, 2018). Furthermore, the role of externalities on economies and water sensitive sectors such as agriculture are not visibly acknowledged by IWRM. High differences between virtual water imports and exports within and between blue and green water types offer an interesting case to consider such externalities.

2.6.2 Externalities to Systems: The Case of Virtual Water Trade

Considering differences greater than 50% between virtual water imports and exports as a threshold (Figure 2.6b), regions where higher volumes of blue and green water are imported than exported and vice versa are identified. Notable examples with high percent imports include the Middle East and parts of Northern Europe and Asia, whereby Australia, India, and Argentina show high percent exports relative to imports. Fewer countries also show high differences in type of virtual water, whereby virtual water imports and exports are predominantly from opposite sources. For example, parts of Southeast Asia, Central America, and Africa export a much higher percent of green water through agricultural products than imported and import higher percentages of blue water relative to export. Countries such as Turkey, Egypt, and Mauritania illustrate the opposite case.

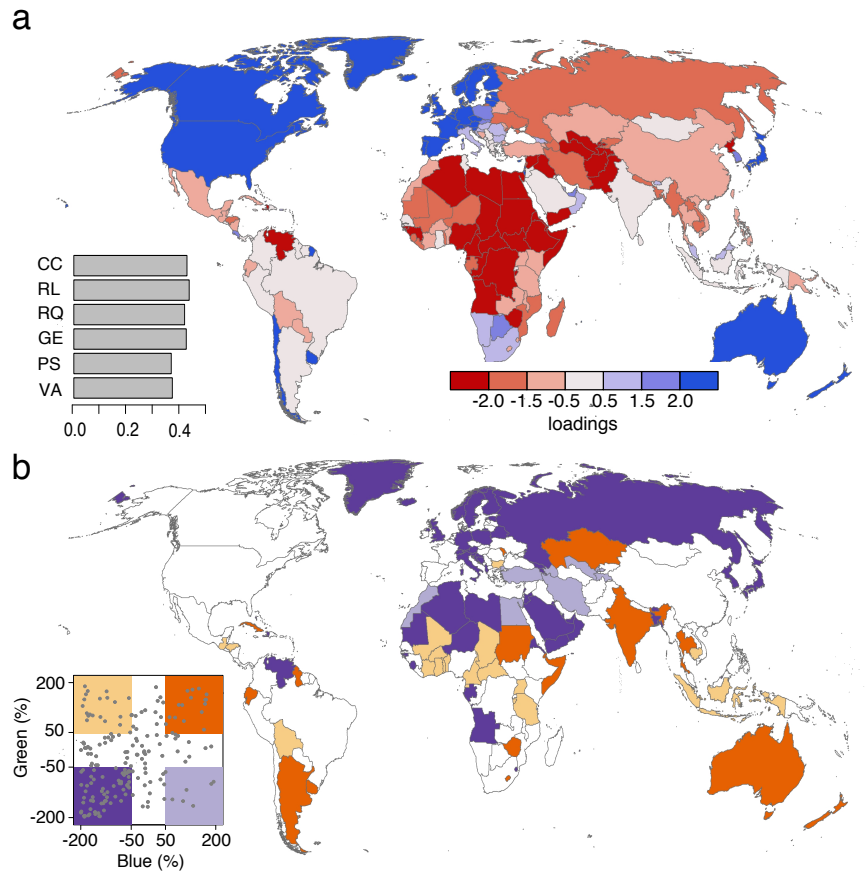


Figure 2.6: Relationship between the leading statistical pattern of governance and blue and green virtual water flux a) Leading statistical pattern of governance. Plot shows the correlation of WGI with the pattern. b) Countries exhibiting high ($\pm 50\%$) differences between export and import volumes. Top left and bottom right quadrants exhibit large differences between blue and green water and top right and bottom left show similarities. Percent difference expressed as $\frac{\text{Export}-\text{Import}}{(\text{Export}+\text{Import})} \times 100$

Furthermore, 66 (61.7%) of the countries with high percent differences are characterized by weaker governance (Figure 2.2b).

Factors that make a country more sensitive to changes in precipitation, trade, demographics, and management decisions at different scales may be exacerbated by weaker governance. For example, precipitation changes may redistribute storage between blue and green water, with strategies for adaptation differing depending on context (e.g Eekhout et al., 2018). Stewardship is informed by such externalities by drawing explicit attention to scale of management, system interlinkages, adaptive solutions, and the role of governance

arrangements in anticipating and responding to risk. Understanding the nature of change and adjusting to the impacts of change as well as the impacts of management decisions is necessary to navigate transitions, especially in light of highly connected globalized systems. While case studies illustrate the efforts of IWRM to coordinate across-scales, explicit attention to concepts such as virtual water trade and external shocks are absent from the case studies. WGI and virtual water indices offer an example of how organized knowledges regarding interlinkages and change over time can inform a stewardship approach.

2.7 Summary and Conclusions

The SES is increasingly subject to a range of natural and anthropogenic changes, with degradation and negative impacts prompting attention towards balancing human and ecosystem needs. Declarations for water and resource management coupled with scholarly pursuits across disciplinary arenas represent a shift in priorities, with increased attention given towards human-environmental interlinkages within and among systems, participatory approaches, and governance. However, efforts towards addressing equity in existing approaches have been narrowly focused. Water Resources Stewardship fills this gap by decomposing the SES into 6 interlinked components that together enable progress towards equitable outcomes. Here, appraisal of IWRM and national-level indicators as water sector approaches have offered insights into limitations while informing the stewardship approach.

1. Stewardship enables equity by delineating human and environmental needs, values, and knowledges on an ongoing basis, allowing for iterative reappraisal of system elements. Changes and perturbations to the system offer opportunities for learning, with understanding how linkages among features may enhance risks to people across scales or reduce adaptive capacities. Stewardship prompts adjustment to governance elements and management actions to ensure progress towards equity. As such, stewardship calls for the addition of governance representativeness in facilitating equitable outcomes.

2. Aspirational goals for equity are present in IWRM literature but regional cross-comparisons of cases underscores the limitations of the approach in practice. While IWRM has successfully prompted a shift towards participatory language in legislation and in how interlinkages among water and other sectors are conceptualized across scales, IWRM lacks explicit attention to the inclusion of underrepresented group and their knowledges. Narrow framings of human-environmental interlinkages and lack of capacity building activities appear to undermine efforts for stakeholder representativeness. Furthermore, a lack of commitment and consistent funding mechanisms for monitoring limits the ability to detect change and adjust strategies for achieving set objectives. Despite contextual differences, IWRM as currently envisioned lacks the tractability to address complex problems with multiple human and environmental objectives. However, stewardship offers a way towards addressing shortcomings.

3. Analysis of water-based and governance indicators underscores how interactions between local characteristics and externalities may exacerbate vulnerabilities if not accounted for. Such externalities are not explicitly acknowledged or addressed by IWRM, providing an opportunity to inform a stewardship approach. Results show that governance indicators vary with similar weights across regions, with the statistical leading pattern of governance characterizing the overall strength of governance. Furthermore, high disparities in virtual water flux is disproportionately present in countries with weaker governance scores. This underscores how identifying externalities and linkages to local contexts presents opportunities to anticipate and adjust to the impacts of change. As indicators are a form of knowledge organization, stewardship enables the development of indicators that are locally-responsive to peoples, their values, and needs to track change and relationships over time.

4. Stewardship presents a novel, timely, and salient approach to address multiple objective problems in an equitable manner that often lack specificity or are absent in current approaches. By drawing from aspirational declarations and work across disciplinary arenas, stewardship organizes existing knowledge while fortifying local solutions. It is noted that stewardship is not a panacea, and efforts to superimpose elements in a top-down manner will likely encounter many of the barriers seen in IWRM implementation. Rather, stewardship offers a new conceptualization of SES, drawing explicit attention to elements that are often subsumed under governance, thereby often overlooked. It is important to acknowledge that there may be limitations in over-allocated systems, developing countries, highly regulated systems, and locations with weak governance. However, by building an ethic of responsibility, stewardship promotes incremental progress towards equitable outcomes constituting an important contribution to addressing current and emerging challenges.

CHAPTER 3
ADAPTIVE POLICY IN TIMES OF CHANGE: MAINE'S
ENVIRONMENTAL FLOW RULE

3.1 Chapter Abstract

Efforts to broaden water allocation beyond consumptive use concerns have led to the development of environmental flow policies. Environmental flows refer to the quantity of water needed to sustain ecosystems, and can be constituted by characteristics of magnitude, timing, frequency, duration, and rate of change. Environmental flow rules set thresholds for water extraction that when exceeded in large volumes can lead to stressed ecosystems, water quality declines, and inequities in water access. At the state-level, these rules face constraints due to a diversity of water users, existing rules and laws, knowledge gaps, and lack of mechanisms for adaptation. Changing hydrologic baselines and water-use changes may render these rules obsolete due to policy inflexibility. Here, a retrospective analysis of Maine Chapter 587: In-stream Flows and Lake and Pond Water Levels is presented. The rulemaking structure is delineated and analyzed to understand the sequencing and co-evolution of processes to identify a) conditions and triggers leading to rulemaking, and b) constraints and opportunities for integrating adaptive elements. The rulemaking process is decomposed into key activities including review of existing laws and rules, acquisition of knowledge, stakeholder participation processes, actions by the Maine Legislature, agency responsiveness, and implementation of the rule. In light of a recent proposal for a new water governance institution, policy uptake of knowledge, opportunities for learning, and stakeholder capacity are identified as important elements that require reappraisal.

3.2 Introduction

Ecological systems are dependent on freshwater to sustain habitat, aquatic health, and the provision of a range of benefits to human systems including resource provision, water filtration, flood attenuation, recreation, and social and cultural practices (Brauman et al., 2007; Green et al., 2015b). Acknowledgement of the role of flow variability to ecological health has led to statutory and regulatory changes at the state-level (e.g. Kendy et al., 2012) to enable the development of environmental flow rules (Annear et al., 2004). These rules set thresholds for water use that when exceeded may result in ecological degradation, conflicts among users, and water scarcity. The State of Maine *Chapter 587: In-stream Flows and Lake and Pond Water Levels* (2007) is a seasonally varying flow rule that seeks to balance ecological health and a broad range of human needs (Appendix B). Rules operationalize and provide technical details to laws (Kerwin and Furlong, 2019) and in contrast to many project or site-specific applications (e.g. Arthington, 2012), are characterized by a level of permanence within a governance system to provide certainty to society (Green et al., 2015a; Frohlich et al., 2018). However, in-stream flow rules are frequently based on historical hydrologic conditions and lack clear mechanisms for adjustment. Hydrologic and water use changes both in the case of Maine (Jacobson et al., 2009b) and elsewhere (e.g. Walsh et al., 2014) threaten to render them ineffective due to rule inflexibility. Therefore, there is a need for an integration of adaptive approaches in policy design and implementation to anticipate and avoid negative consequences.

Adaptive management refers to the process of reducing uncertainty in complex systems through the design and application of diagnostic experiments (Holling, 1978). Often referred to as ‘learning by doing’, adaptive management has been incorporated into a range of flow management approaches to contend with changing conditions and uncertainties about system dynamics (Poff et al., 2010; Arthington, 2012; Allan and Watts, 2018). Planning at the state-level scale broadens the variety of contexts, water uses, and objectives that must be addressed and often results in the adoption of policies that are inherently

tentative. Given that these policies are unable to address the level of system complexity, opportunities for learning and mechanisms for policy adjustment are critical components (Holling, 1978). However, the structure of governance in relation to environmental problems presents a range of challenges. Barriers to integrating adaptive elements into policies include regulatory fragmentation, legal constraints, narrow agency mandates, knowledge deficits, lack of knowledge integration into policy, and limited stakeholder participation (see Holling et al., 1995; Pahl-Wostl and Kranz, 2010; Frohlich et al., 2018). While these factors may constrain rule content, system stress or failure reveal existing governance shortcomings and may prompt a variety of adjustments (Birkland, 1998; Prokopy et al., 2014; Newig et al., 2019). Identifying opportunities for initiating change as well as potential barriers and tensions are necessary for informing rulemaking under changing conditions.

There are concerns that flow rules that are fixed are too restrictive, limit ecosystem protection, and are inadequate for addressing the particularities of place-based contexts (e.g. Arthington et al., 2006). However, the governance structure of state-level planning inherently requires a level of compromise among objectives, with rulemaking presenting a valuable tool to accomplish ecological goals within a use context. While reassessment on an ongoing basis is critically absent, these rules carry the strength of law and represent a social commitment to balancing needs in the future. Here, a historical retrospective of Maine Chapter 587 (hereafter Ch. 587) is presented, providing a 'test-bed' to understand and improve transitions to change, knowledge processes, and opportunities for learning to foster adaptation in the state. This rule seeks to balance human and ecological needs but requires reappraisal due to changing baselines. First, an overview of the Maine state context from the perspective of hydrologic change, flow policies, and water governance is presented. Next, the rulemaking process is retrospectively delineated, with focus on a) events and conditions that prompted policy action, b) characterization of opportunities for learning and barriers to addressing change within the rulemaking process, and c) identification of ongoing challenges that could potentially be harnessed in the context of

emerging water management institutions in the state. Finally, key lessons and recommendations for future rulemaking processes are offered.

3.3 The Maine State Context

3.3.1 Physical Background

Maine is divided up into three climate divisions exhibiting a range of variability in precipitation and temperatures across the state. The Northern, Southern Interior, and Coastal divisions comprise 54%, 34%, and 15% of the state respectively, with average annual temperature and precipitation higher in the Coastal division and lower in the Northern (Jacobson et al., 2009a). While variations exist among divisions, Maine is characterized by cold winters and mild summers with an equal distribution of precipitation throughout the year with an average of 44.8 in per year (1980-2019; National Oceanic and Atmospheric Administration, 2019). Streamflow varies seasonally with peak flows in spring, low flows in summer, and increasing flows in fall. High flows in spring (April-May) are driven by precipitation and snowmelt, while groundwater provides baseflow to streams in the summer when precipitation is lower and temperatures increase (Hodgkins et al., 2005). However, Maine has experienced changes within the hydrologic system with changes in seasonality (Figure C.1). Trends in streamflow show an increase in spring flows and decreases in low flow during summer months (Hart et al., 2009), driven by increases in spring rainfall (Hodgkins and Dudley, 2006) and temperature increases. Shifts towards earlier annual maximum precipitation have also been observed across the state (Dhakal et al., 2015). Both precipitation and temperature change have an impact on the seasonal cycle of streamflow in the state, with implications for ecological and human systems (Jacobson et al., 2009b).

Regulation of streamflow in Maine has been historically focused on fish species of state and federal significance. Diadromous fish are highly active throughout the year with high Atlantic Salmon and alewife activity exhibited throughout the spring to summer period

(Saunders et al., 2006). Federal-level projects, permitting, and hydropower licensing have been opportunities for application of minimum low flow standards through the U.S. Fish and Wildlife Service (USFWS) Northern New England Flow Policy (1981). While additional standards may be provided during spawning and incubation periods, the policy at minimum recommends maintaining the August median low flow level. Application of regulations such as the USFWS Endangered Species Act (ESA) is often accompanied by flow alteration limitations to promote habitat and species recovery. The U.S. Atlantic salmon only occurs in Maine waters and was listed under the ESA in 2000 and expanded in 2009 due to decades of declining populations. Maine waters are categorized by water quality to support habitat and safe use by the Maine Water Classification Program (1985; 38 M.R.S.A Article 4-A). At the highest standard (AA), waters with ‘outstanding ecological, social, scenic, or recreational importance’ are afforded higher quality protections, including those historically populated by Atlantic salmon. The law characterizes AA surface waters as being ‘free-flowing and natural’ acknowledging the relationship between water quality and quantity, but falling short of setting flow standards.

3.3.2 Governance Background

Maine has relatively few laws concerning water quantity, with most limitations on use concerning domestic use and hydropower. Key statutes include: a) groundwater priority for domestic uses (38 MRSA §404), b) transport of surface and groundwater water (22 MRSA §2660-A), and c) construction of dams or other activities on select waters with high significance to the state (12 M.R.S.A §403; 38 M.R.S.A article 5-A). In 2002, the Legislature passed the Water Use Reporting Program (38 M.R.S.A. §470) to require the collection, compilation, and sharing of water use data across water-related agencies in the state. Withdrawals are reported according to daily thresholds based on watershed size for surface extractions and distance from surface water body for groundwater. The Water Classification Program (1985) and Water Use Reporting Program (2002) contribute to

characterizing Maine waters according to quality and risk for over-extraction (e.g. Maine Geological Survey, 2007), respectively. They thus provide a basis for setting water management objectives and identifying risks to surface waters.

The lack of comprehensive rules and regulations for water management have led to attempts to address shortcomings as conflict arise over time. However, water management responsibilities are spread across several agencies (Table 3.1) requiring coordination across jurisdictions. Note that agency names used throughout are as they were during Ch. 587 rulemaking. A 2012 restructuring of the state government led to agency mergers and name changes. Coordination with federal entities is also necessary for compliance with regulations, access to financing, and monitoring and data support. For example, the Natural Resources Conservation Service (NRCS) works closely with the Maine Department of Agriculture to set policy goals and offer technical and financial support, while the Environmental Protection Agency oversees water quality under the Clean Water Act (CWA) and Safe Drinking Water Act (SDWA). While federal regulations fill gaps in water management by setting minimum standards, the lack of a centralized water authority at the state-level often results in asymmetries across jurisdictions. Notably, the Land Use Regulation Commission (LURC) issues flow requirements through permitting processes within their jurisdiction while the Department of Environmental Protection (DEP) does not. Interplay across levels creates a complex set of interacting policies (Young, 2013), with each entity given the authority to engage in water-related rulemaking at the state-level while complying with federal regulations. This increases the level of complexity in designing and implementing new water laws and subsequent rules. Furthermore, Maine's Administrative Procedures Act (APA; 5 M.R.S.A. §8001-11116) provides the Legislature with the authority to review rules (denoted as 'major substantive'), which can impose further limitations on their scope and content (see Section C.2 for details). The underlying legal system governing water allocation complicates these efforts as resulting rules must also avoid violating existing water rights (MacDonnell, 2009; Hurst, 2015). In particular,

Table 3.1: Select Federal and State Water Management Agencies and Organizations (pre-2012)

Issue	Federal Level	State Level
Water Quality	Environmental Protection Agency	Dept. of Environmental Protection Land Use Regulation Commission ¹
Drinking Water	Environmental Protection Agency	Drinking Water Program (Dept. of Health and Human Services)
Ecological	U.S. Fish and Wildlife Service National Marine Fisheries Service	Dept. of Inland Fish and Wildlife Atlantic Salmon Commission
Agriculture	Natural Resources Conservation Service (U.S. Dept. of Agriculture)	Dept. of Agriculture, Food, and Rural Resources
Hydrologic Data	U.S. Geological Survey	Maine Geological Survey

¹ Responsible for planning in Maine's 1.4 million acres of unorganized lands.

water utility charters are codified in Maine's Private & Special Laws and contain rights to access specific water sources. Therefore, the dynamics among a) existing laws and rules, b) asymmetries across jurisdictions, c) compliance with federal regulations, and d) legal water rights must be considered throughout the rulemaking process.

Previous attempts to address water management fragmentation at the state-level has failed to gain traction. In the late 1980s, a series of studies were conducted to assess the adequacy of Maine's water laws for ensuring supply in the future. Reports by Public Utilities Commission (1988) and the Water Supply Study Commission (1989) found a) water suppliers and users perceive low risk to water source over-extraction, b) water laws do not adequately consider surface and groundwater as an interlinked system, c) a lack of coordination among water management entities, and d) low data availability on supply and use. While recommendations to address these shortcomings were made to the Legislature, few gains were made at the time - the water reporting law was introduced over a decade later. This historical context highlights a) the role of governance structure in constraining or facilitating rulemaking and b) consideration of factors that may lead to policy action.

3.4 Driving Factors of Policy Action

Policy action arises due to a need to address a problem due to identification of institutional shortcomings or new or changing conditions (Kerwin and Furlong, 2019). However, gradual change or new information alone are often not enough to prompt policy change, as evidenced by the range of environmental problems that go un-addressed (Birkland, 1998). Rather, policy action occurs in response to some event that reveals inadequacies or failures within the existing governance system. A ‘focusing-event’ is a sudden, relatively uncommon, event that can be defined as harmful or potentially harmful and is perceived as an impetus for policy-making (Birkland, 1998). These events disrupt the normal policy environment, and create windows of opportunity, or ‘policy-windows’ where the likelihood of enacting change is higher than normal for a short period of time (Michaels et al., 2006). Prokopy et al. (2014) offer a broader definition of these events, noting that a range of events such as disasters, planned actions such as proposed projects, government regulation, new technology or information, and financing can act as catalysts to change under the right underlying conditions. For example, the availability of financing may facilitate the formation of new water management institutions. However, the perception of harm is often effective in drawing attention towards an issue where a governance solution is likely to mitigate future risks. As such, it is important to identify not only catalysts, but the factors from a governance perspective that may enable or impede policy adjustment.

3.5 Maine Chapter 587 Rulemaking

Maine Chapter 587 drafting began as an inter-agency activity in 1999, with a formal rulemaking process authorized by the Legislature in 2002. Here the rulemaking process is delineated into pre, during, and post-rulemaking periods to identify and characterize a) the events and underlying factors leading to Ch. 587 rulemaking, b) the structure and process of Ch. 587 rulemaking including constraints and opportunities for addressing gaps, and c) ongoing challenges that may be addressed in future policy processes.

3.5.1 Pre-Rulemaking

From 1999-2002, Maine experienced below-average precipitation with severe drought conditions (2001-2002), resulting in reduction in streamflow levels, reduced groundwater recharge, and impacts to aquatic ecosystems, agriculture, and public water supplies (Lombard, 2004b). By the end of 2002, thirty-five public water systems had been affected, with severe shortages experienced by smaller community systems. Additionally, 17,000 private wells were reported dry in 2002 due to low groundwater levels (Maine Emergency Management Agency, 2002). Agricultural losses between 2001-2002 totalled over \$32 million, with high losses reported for blueberry crops (Lombard, 2004b). Concern for ecological impacts were also high, with the combination of drought and human demand leading to ecological degradation. In 1999, the Governor directed the Department of Agriculture to develop a management plan to assist farmers in reducing their drought risk. This included financial and technical assistance, expansion of irrigation, development of wells, and construction of storage ponds (Maine Department of Agriculture, 2002). However, the proposed expansion of irrigation caused concern from other agencies regarding the potential impacts to fish, particularly as the drought continued (DEP, 2000).

As noted in the 1980s, the state failed to take action on the recommendations for addressing Maine's fragmented water management system. Increased perception of risk or uncertainty regarding future supply has been shown to prompt attention towards new information and planning strategies (e.g. Lowrey et al., 2009). The noted low perception of risk among users may have contributed to lack of policy action in response to the report recommendations. Conversely, the 1999-2002 drought appears to have acted as a 'focusing-event' by exposing supply vulnerabilities across multiple sectors, and drawing public and policymaker attention towards gaps. Single agency responses to the drought, such as the planned expansion of irrigation by the Department of Agriculture can be characterized as unintentional catalysts which prompted additional concerns regarding impacts to streamflow, water quality, and aquatic habitat. However, federal-level financing

for irrigation upgrades and water development likely contributed to the content of this plan, highlighting the role of funding availability for catalyzing actions (Prokopy et al., 2014). Imposition of federal regulation via the Atlantic salmon listing coincided with these events, adding both additional uncertainty for future water supply access, and prompting multi-level coordination in regards to species recovery. Therefore, the drought appears to have triggered a set of cascading catalyst events ultimately leading to in-stream rulemaking as a way to balance human and ecological water needs.

3.5.2 Rulemaking

The Ch. 587 rulemaking process was comprised of a series of co-evolving activities involving agencies, stakeholders, and the legislature to identify existing policy gaps, stakeholder needs, and new information needed to develop in-stream flow rules. Understanding the timing, relative intensity, and dependencies of various activities is necessary for identifying elements that advance or impede the rulemaking process. Here we adapt a graphical synthesis of an environmental assessment process from Holling (1978, pg. 39) to include attributes of the rulemaking process we believe require more attention (Figure 3.1). While subjective, these attributes most closely relate to the standard rulemaking procedure in the state of Maine (Figure C.1). The relative timing and intensity of these elements were derived from a review of rulemaking documents, legislation, and scientific reports. While Holling (1978) describes a focused 1-year activity, application of this frame to a rulemaking process leads to better delineation and analysis. A full timeline of events is provided in Table C.1.

Rulemaking activities are comprised of a) review of existing laws and rules to identify gaps and legal constraints, b) acquisition of scientific information to inform and aid in rule implementation, c) stakeholder participation activities including formal workshops and public commenting opportunities, d) agency responsiveness which refers to agency actions in response to new information, stakeholder input, or by the direction of the Legislature, e)

Legislative action comprising of formal rule review and re-authorization of the in-stream flow statute, and f) implementation of the rule. Each is explained in further detail below. Figure 3.1 indicates that rulemaking activities overlap through time yet show a distinct pattern of activity initiation, pause, and restart. For example, the majority of the activity occurs between the years of 1999 and 2005 which is characterized by pre-proposal and draft development stages, with each subsequent activity beginning after the previous one. Ch. 587, like many rulemaking processes, began with internal agency review of existing rules and laws to inform rule scope and applicability, and identify critical gaps. The identification of key knowledge gaps therefore prompts the development of scientific information to both inform rule content and aid in implementation. Likewise, action by the legislature across different periods induces a pause in other activities with few actions taking place during the legislative review of a rule draft. However, decisions to send the rule back to the DEP or imposition of additional conditions prompts renewed cycles of stakeholder and agency activities.

The rule was ultimately approved in June 2007 after two rounds of public comment (February 2005 and June 2006) and a Public Utilities Commission (PUC) inquiry into economic impacts for water utilities (November 2006). Rulemaking considers a broad array of objectives and requires a different level of cooperation than in site-specific flow studies. Therefore, tensions among scientific knowledge, ecological goals, human uses, and various stakeholder perceptions and concerns may act to constrain the rulemaking process. In the following sections, we consider each attribute in the rulemaking process and provide key examples of tensions and opportunities for overcoming shortcomings.

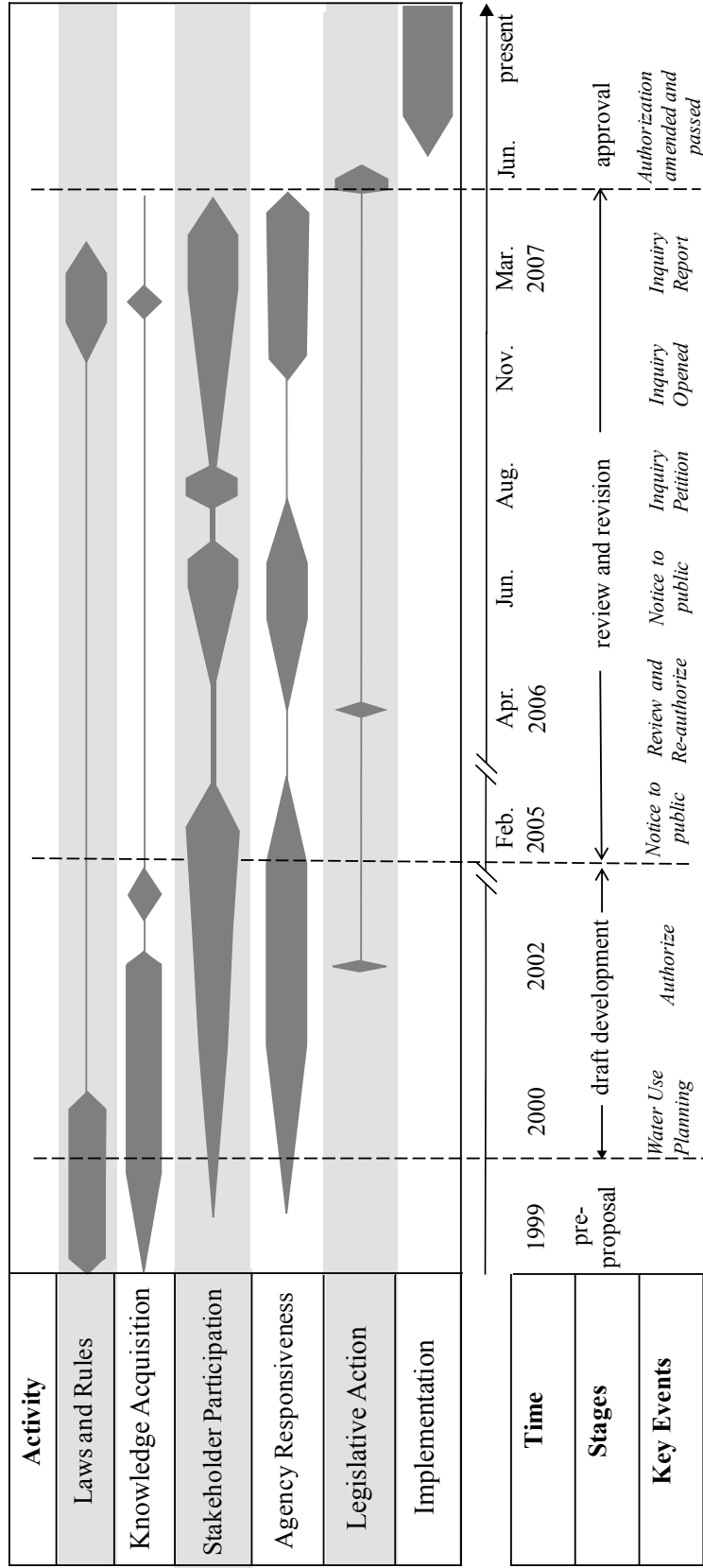


Figure 3.1: Timeline and relative importance of activities for the Chapter 587 rulemaking process. Key events that occurred in each stage of the process are noted.

3.5.2.1 Governance Structure and Existing Rules

A host of state and federal agencies were involved in Ch. 587 rulemaking due to the nature of Maine's water governance system (Figure 3.2). While the rule is not directly tied to any federal regulations, it must not pose negative impacts to the directives of other federal and state agencies sharing jurisdiction within the state. As such, agencies that are less directly involved in water management occupied advisory roles. For example, the ESA listing for the Atlantic salmon necessitated coordination with USFWS, NOAA National Marine Fisheries Service, and state-level wildlife agencies to ensure compliance. Given the multiple jurisdictions and existing state and federal policies involved, a review of existing rules and identification of policy constraints was determined early within the process. Constraints on the agency ability to pursue rulemaking for in-stream flows stems in part from the lack of clarity in federal regulations regarding water quantity. The CWA and SDWA set minimum standards for water quality and provide a vehicle for states to implement laws that expand water quality protections. For example, Maine's Water Classification Program (38 M.R.S.A. Article 4-A) exceeds the standards of the CWA and ties water quality to a range of riverine values. Management of the Pollutant Discharge Elimination System ensures the standards are met in accordance with both federal regulations and state statutes. The DEP intended to pursue in-stream flow rules under the classification program due to presence of flow language. However, the State Legislature determined flow rules to be outside the scope of the law. The CWA does not explicitly allow for in-stream flows and does not supersede governance of water quantity and allocations [33 U.S.C. §1251(g)] insofar as it does not violate quality standards. The ambiguity of how to mobilize a flow rule was further enhanced by the asymmetries in how the LURC prescribed flow requirements when issuing permits while the DEP did not. Rather than filling this gap with a consistent permitting process, the Legislature prohibited the imposition of further regulation through permitting mechanisms.

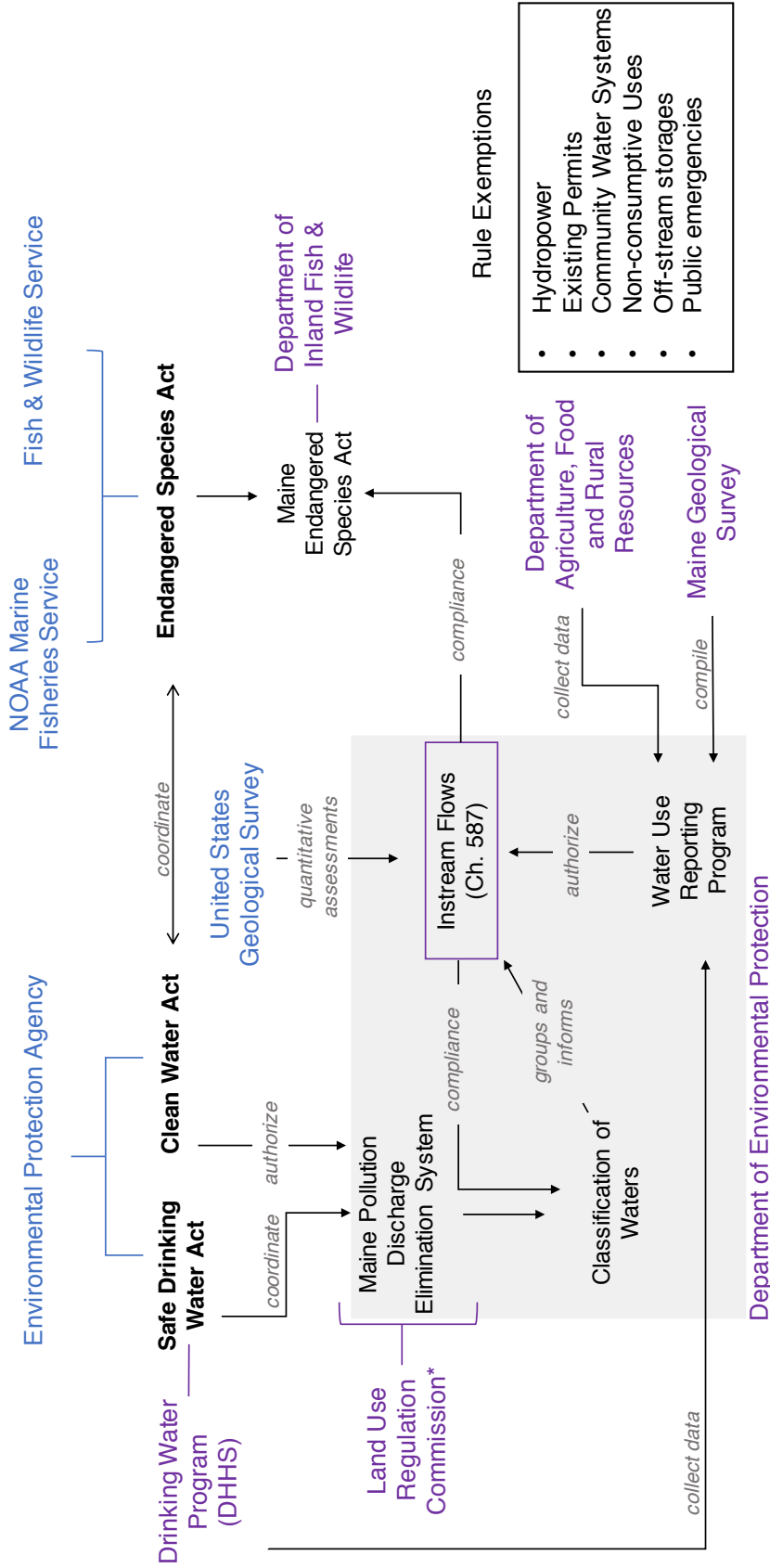


Figure 3.2: Jurisdiction of selected federal and state agencies for water quality and quantity management relating to Chapter 587. Blue and purple text denote federal and state agencies respectively. Exemptions to Ch. 587 compliance are noted. This does not present an exhaustive depiction of involved agencies. Additional entities included the Atlantic Salmon Commission, Office of the Public Advocate, Natural Resource Conservation Service, the Public Utilities Commission, and the State Planning Office. *The Land Use Regulation Commission (now Land Use Planning Commission) issues permits in Maine's unincorporated lands.

While early DEP discussions emphasized the need for a clear method of determining compliance, the lack of a permitting mechanism posed a barrier. The establishment of the Water Use Reporting Program facilitated the aggregation of water use data from other agencies including the Drinking Water Program, Department of Agriculture, LURC, and the DEP by the Maine Geological Survey (MGS). In a limited way, the collection of this data provided a level of water supply monitoring but did not directly monitor Ch. 587 compliance. As such, Ch. 587 is situated within an existing system, and with the exception of the Water Use Reporting Program, did not constitute a restructuring of water governance in the state. Therefore, while this process filled some of the gaps indicated in the late 1980s supply studies, key challenges remain: one notable example is a lack of consideration to groundwater and surface water interlinkages. As with permitting, groundwater regulation was not considered during the process.

In-stream flow rules are authorized (38 M.R.S.A. §470-H) under the Water Use Reporting Program (2002). The Legislature designated these rules as ‘major substantive’, requiring approval. Conditions on rule content placed by the legislature were a) a new permitting system could not be established, b) existing permits could not be affected, c) exemptions for hydropower and commercial water bottling sourced from groundwater, and d) no water rights could be granted. Existing rules and laws were reviewed towards the end of the process to ensure that water utilities would not be in violation of their charters and that rate changes could be petitioned if needed for compliance. While analysis of the existing water governance system identified key gaps and opportunities for redressing shortcomings, the Ch. 587 process was constrained by the existing structure with no pathway for adjusting the structure of governance. As noted within a DEP working group, the in-stream flow rule had to be capable of approval by the Legislature and acceptable to users (DEP, 1998). This consideration of pragmatism inherently narrowed the ambitions of the rule and limited the ability to integrate scientific information, address broader water governance issues, and monitor compliance.

3.5.2.2 Knowledge Acquisition

The types of knowledge generally used to support policy development include scientific information, identification of stakeholder priorities and values, and experiential knowledge. Here, knowledge is limited to the analysis of hydrologic information. While there are a range of relationships among people and flow variability, including social and cultural practices (e.g. Jackson et al., 2015), the Ch. 587 process treated knowledge in a more restrictive manner. Knowledge activities began early in the proposal process due to the identification of significant knowledge gaps on streamflow and water use in the state. Existing low flow policies such as the USFWS New England Flow Policy provided an initial starting point for the rule standards. However, this policy is inadequate in providing the flow variability needed by a range of fish species in the state (e.g. Saunders et al., 2006). Recent research regarding the importance of the environmental flow regime (e.g. Poff et al., 1997) coupled with the Atlantic salmon concerns further underscored this gap in existing policies. However, tensions between ecological needs, financial constraints, data availability, and the interests of a range of water users constrained the level to which a state-wide flow rule could harness ecological knowledge.

One key example of this tension was the use of a 7Q10 standard in a low flow policy developed for Aroostook county in response to irrigation impacts to fish (Aroostook Water and Soil Management Board, 1996). While the 7Q10 standard has been used as a flow standard in several states (Annear et al., 2004), it originated as a 'worst-case scenario' water quality standard, whereby pollutant discharges would require a minimum volume to avoid water quality violations. The prolonged use of 7Q10 as an annual standard has been shown to cause fish mortality and stream degradation. Despite this, due to its ease of use its uptake was viewed as one way to compromise between farmers and ecological needs. During an early stakeholder meeting, the Aroostook low flow policy was raised as a potential approach, underscoring the gaps between science and policy. However, the application of other environmental flow approaches that are more ecologically responsive

(Table C.2) face limitations due to the complexity of state-level planning and data and financial constraints. Ch. 587 ultimately compromises by offering a threshold level of flow protection but allowing for some level of variability through seasonal standards (Table 3.2). Categorizing flow by the classification program, the amount of alteration varies with quality class, with limitations on withdrawals when flow is less than the seasonal standard (see Appendix B). As such, flow alteration is minimized on class AA and A rivers which are of higher ‘value’ to the state.

Table 3.2: Chapter 587 Seasonal Aquatic Base Flow Standards

Ch. 587 Season	Dates	Historical Median Flow
Fall	September 16 - November 15	October
Early Winter	November 16 - December 31	December
Winter	January 1 - March 15	February
Spring	March 16 - May 15	April
Early Summer	May 16 - June 30	June
Summer	July 1 - September 15	August

As previously noted, Maine has historically lacked data on both water use and hydrologic conditions. The Water Use Reporting Program provided a mechanism to prompt data collection, aggregation, and enable identification of user groups, areas, and times of the year with high water use. However, a lack of updated streamflow estimates (Hayes and Morrill, 1970; Parker, 1977) for streamflow undermined the ability of the DEP to quantify water supply and set effective flow standards. This knowledge gap prompted the DEP and cooperating agencies to finance U. S. Geological Survey (USGS) streamflow studies for Maine between 2000-2004. Regression equations relating streamflow to basin characteristics were used to estimate median monthly streamflows in ungaged basins for use in estimating flow standards where data were absent. These studies narrowed a critical knowledge gap in Maine but due to financial constraints, deficits exist for smaller basins in the state (Table C.3). The production of this new information subsequently enabled the Maine Geological Survey to assess potential over-allocation risk to watersheds based on the

new flow standards and data through the Water Use Data Program [38 M.R.S.A. §470; (Maine Geological Survey, 2007)]. It also was mobilized later in the process in response to economic concerns from water utilities (see Section 3.5.2.4). While these knowledge activities further enabled policy development, the lack of attention to changing hydroclimatic baselines poses challenges for the policy due the absence of a mechanism for triggering the uptake of new knowledge.

3.5.2.3 Stakeholder Participation

The level to which participants influence policy varies, even in the presence of formalized opportunities for stakeholder input (National Research Council (NRC), 2004; Reed, 2008). During the pre-draft process, stakeholders were invited to participate in workshops and provide comments on working drafts of the rule. Working groups were formed around interests including aquatic life, public water utilities, agriculture, and other industry and recreation stakeholders (Table 3.3). While a range of stakeholder were present, both the review of existing laws and rules and the initial authorization of the rule led to the exemption of particular uses from the rule. For example, a commercial water bottler was effectively exempt as their water source is groundwater, which was largely unaffected by the rule. As such, emphasis was placed on water utilities and agriculture as the largest water use groups in the state. Initial drafts of the policy went through inter-agency review and were circulated to select stakeholders, but were not accessible to the public prior to the public commenting period. The stakeholder process became more formalized with the authorization of rulemaking by the legislature in 2002. Participation peaks at the public commenting stage, but it is unclear to what extent public comments influenced rule content versus participation in workshops. However, research at both the state and federal levels have shown that stakeholder input has a stronger uptake into policy content during pre-draft periods (Rinfret, 2011; Rinfret et al., 2014; Crow et al., 2017). Stakeholder participation peaked again in June 2006 in response to another round of

Table 3.3: Stakeholder Groups Involved in Chapter 587 Rulemaking

Federal Agencies	State Agencies	Environmental
Recreation	Industry	Agriculture
Public Water Supplies	Commercial Water	Bottling

stakeholder meetings and commenting prompted by the legislature. In both cases, the perception that the rulemaking process had not adequately responded to the needs of stakeholders prompted a continuation of the drafting process.

The diversity of needs raised by agriculture and water utilities reflect the variety of constraints that had to be considered when designing the rule. For agricultural users, irrigation demand tends to be highest during low-flow periods, a time where ecological needs and human use are most in conflict. A early stakeholder meeting in 2000 indicated that key concerns for agriculture were financing for water storage infrastructure, a rule that would be easy to apply, predictability in the regulatory process, and technical assistance (Sustainable Water Withdrawal Policy Work Group, July 19, 2000). Options such as water storage infrastructure and groundwater sourcing may alleviate concerns but are not equally available to farmers based on siting and financing. This is particularly true for northern Maine where groundwater availability is low, in contrast to coastal Maine where access is higher (Maine Geological Survey, 2007). A similar diversity exists among water utilities with some depending on groundwater that may be slower to recover from droughts, as well as varying financial capacities and resources. However, the water utility sector as a whole had access to an alternative process through the PUC to petition an inquiry into economic impacts of the rule (Docket No. 2006-481). This mechanism enabled further alteration of the rule towards the end of the process, raising questions regarding the level of influence different stakeholders may possess within the rulemaking process.

Opportunities for identifying the needs of various stakeholders is essential for designing an effective rule as well as ensuring policies will not have unanticipated negative impacts. Furthermore, these differing factors may impact how people perceived risk of future

drought conditions and to what level they believe water policy in the state requires reappraisal. Understanding these unique features may open up pathways to communicate risk (e.g. Niles et al., 2013) and identify strategies needed to help regulated communities adapt to new policies.

3.5.2.4 Agency Responsiveness

As noted above, agency responsiveness to stakeholder input has been shown to vary across the stages of the rulemaking process and shows dependency with the other activities. In April 2005, the Legislature sent the rule back for revision due to unresolved conflicts between the rule and water users. This directly led to another sustained period of agency activity. Likewise, the actions by water utility stakeholder groups prompted additional agency activity as part of a focused inquiry into economic impacts. As noted above, a range of constraints were raised by agricultural users throughout the stakeholder process. However, it is evident from the actions of the Legislature that conflicts remained after the initial draft of Ch. 587 was submitted for review. One key tension was the capacity for stakeholder groups to adapt to a new policy, particularly in the direct aftermath of the drought. The Agricultural Water Management Board (AWMB; 7 M.R.S.A. §352-353) was established in 2005 to coordinate with the DEP in developing water sources for agriculture that are environmentally and economically sound. This governance adjustment facilitated the implementation of a new policy but also is an effort to raise the capacity of farmers to respond to water stress while reducing their impact on aquatic ecosystems.

Likewise, the PUC inquiry was directly in response to the concerns of water utilities, holding workshops to estimate standards and estimate fiscal investments needed for select utilities. One key finding was that there were uncertainties in both the rule standards and implementation. The outcome was the addition of a clause in the rule that exempted community water systems from compliance if they could not reasonably meet flow standards while operating within their design capacity. This exemption also requires that

DEP exemptions were reviewed by the Drinking Water Program, the Office of the Public Advocate, and the PUC to ensure safety, legality, and financial viability respectively. Coordination with agencies that had direct relationships with the regulated groups helped reduce uncertainties about how the rule would be applied. Within the rulemaking process these changes were directly prompted by actions by the Legislature and institutional mechanisms exploited by stakeholders. While from one perspective they placed a barriers on developing a more ecologically responsive rule, they also moved the development of the rule towards compromise. While the scope of the rule was narrowed over the course of the process, stakeholder concessions helped to increase the likelihood of compliance with the final rule.

3.5.2.5 Legislative Action

During the Ch. 587 process key Legislative actions relating to the rule occurred in 2002, 2005, and 2007. As noted above, the Legislature passed the Water Use Reporting Program in 2002 and authorized in-stream flow rules. While the DEP had initially developed rules, the Legislature imposed limitation to rule scope and imposed the condition of review and approval. Legislative rule approval resulted in periods of paused activity and triggered new activities. As shown in Figure 3.1, the April 2005 event occurs largely in isolation, but directly prompts agency activity. A break is shown between February 2005 and April 2006 as the Legislature held review of the rule until the next session, renewed the authorization, and didn't place additional conditions on the rule until April 2006 when it directed the DEP to resolve conflicting uses. While much consideration is given to stakeholder roles within decision-making processes, it is important to consider the role that legislatures may have on the rulemaking process. Depending on context, the structure of the rulemaking process as determined by a state's APA can both constrain and enable activities (Renfrow et al., 1986). In this case, legislative action in 2005 and in 2007 facilitated agency

cooperation and the establishment of an institution to build farmer capacity in context of the rule.

3.5.2.6 Implementation

Ch. 587 was passed by the Maine State Legislature in June 2007 after a nearly decade-long rulemaking process. The resulting rule met all requirements set by the Legislature, provides a seasonally varying standard, and offers exemptions for public emergency and drinking water under drought conditions, non-consumptive uses (38 M.R.S.A §470-A) and off-stream storage. The rule also allows for site-specific flow standards based on flow studies subject to inter-agency review. While public water utilities were provided effective exemptions to the rule, additional resources were generated to facilitate agricultural compliance with the rule as well as reduction of drought risk. Availability of federal funding facilitated water conservation and the development of irrigation efficiency plans (Natural Resources Conservation Service, 2019). At the state-level, the DEP and Department of Agriculture coordinated to secure water source development on a DEP wastewater bond. In 2008, the \$1.5 million bond was passed and disbursed by the AWMB, prompting activities that both encouraged compliance while addressing vulnerabilities highlighted by the drought event. The AWMB also coordinated the DEP, USGS, and MGS on calculating flow limits as part of the rule and offered important technical support for farmers. However, DEP ability to monitor and assess compliance was limited by lack of resources or financing. While the MGS completed studies using USGS equations and used data to identify potential over-allocations, estimates were characterized as having high uncertainties. As a compliance mechanism, more detailed monitoring and reporting would be needed. The long-term implementation of the rule is discussed next.

3.5.3 Post-Rulemaking

Changes in the State Legislature after the 2008 state election have impacted how Ch. 587 is implemented. While the Water Use Reporting Law is still active, agricultural

producers were provided an exemption to reporting in 2011 (38 M.R.S.A §470-C) and no reports have been issued since. A freeze on bonds led the AWMB to cease activities in 2012 (Maine Secretary of State, 2014) and is currently inactive. The lack of data gathering and inactivity of an institution for assisting in rule implementation undermines the effectiveness of the rule. While no official compliance monitoring exists within the rule, water use reports provided one indicator of potential water stress. Their absence reintroduces a knowledge gap and poses a challenge to future water planning.

In 2016, the state was affected by a severe drought but did not exhibit the characteristics of a ‘focusing-event’. Unlike 1999-2002, the 2016 drought and subsequent years were characterized by widespread drought in the summer months but surface water recovery in the fall due to precipitation. While a broad range of users were impacted as in 2001, no policy changes were made despite inquiries into water supply vulnerabilities (e.g. PUC Docket No. 2016-00233). As noted by Prokopy et al. (2014), baseline conditions facilitate catalyst events. It is possible that the lapse in government commitment for enforcing existing water laws was a factor in how the drought was addressed. Furthermore, the persistence of the 1999-2002 event may have increased the perception of risk. Ongoing challenges raised by the inquiry included the vulnerability of smaller water utilities to anticipate and respond to drought conditions. Maine lacks a comprehensive drought management plan, and the PUC only requires drought plans for utilities serving over 3,300 customers. Despite this, no policy changes have been made since the inquiry was opened in 2016.

However, new attention has been brought towards the need for water planning since the 2018 election. In January 2019, a bill was put forth in the Legislature to form an inter-agency and multi-stakeholder Water Resources Planning Committee with the goals of a) assessing risk of over-allocation on the watershed scale, b) development of local water management plans and conflict resolution among users, and c) annual review of existing water laws and rules [L.D. 199 (129th Legis. 2019)]. The bill has broad support from

stakeholders and agencies and if passed will be the first active multi-agency water management entity in over a decade. This presents an opportunity for future policymaking. However, comprehensive reporting and monitoring have been largely unattended in both the rulemaking and post-rulemaking periods. These elements are important to achieve the broader goals and aspirations of Ch. 587 both now and in the future and require attention.

3.6 Conclusions

Rules for in-stream flows offer opportunities to balance a range of human water uses with ecological health at the state-level. These rules carry the force of law and offer a level of permanence for guiding state water governance. Criticisms of rules such as Ch. 587 refer to their fixed and inflexible nature (Arthington et al., 2006). However, the governance structure of state-level planning requires compromise due to constraints and limitations within diverse use contexts. The Maine Ch. 587 offers an unique case regarding the challenges of resolving diverse needs and capacities among water users, addressing critical knowledge gaps, and working within institutional constraints of a rulemaking process. Delineating the rulemaking context into parallel activities helped to disentangle elements and identify ongoing or punctuated events that both constrained and facilitated rule development. While future work is needed to identify commonalities with other state rulemaking contexts through cross-comparisons, the presented work here provides several insights to inform future processes:

1. Changing conditions pose significant challenges to Ch. 587 and similar rules.

Hydroclimatic changes have been well documented at the state-level (Jacobson et al., 2009b), including changes in streamflow seasonality (Hodgkins and Dudley, 2006; Hart et al., 2009). Analysis of daily streamflow trends (Figure C.1) shows significant decreases in streamflow across the state in the late summer period, suggesting continuing conflicts between ecological and human water needs. Reporting and monitoring of conditions was under-addressed during the rulemaking process and

constitutes a knowledge deficit. Attention towards these elements is important for achieving the broader goals and aspirations of in-stream flow rules. Opportunities for learning must be integrated into the rulemaking process.

2. Increasing the capacity of stakeholders to respond to change coincides with opportunities for learning (Dilling et al., 2015). Introduction of institutions such as the Agricultural Water Management Board enable adaptation to new rules while increasing the capacity to respond to periodic water stress. The newly proposed Water Resources Planning Committee offers an future opportunity to address critical knowledge gaps. Infusion of knowledge during the implementation phase of rulemaking that feeds back into knowledge acquisition processes can be used to better identify ‘hotspots’ that require attention. The proposed committee includes a provision for annually reviewing policies, but does not contain an explicit mechanism for knowledge integration. Such processes lead to an increase in the overall capacity of stakeholders due to access to knowledge, data, analyses, and opportunities for building broader understanding of the unique needs and inter-dependencies among people and the environment.
3. In order to achieve more adaptive processes, triggers must be built into policies so that failures are anticipated and avoided. As evidenced by the 2016 drought event, failures do not always catalyze change (Birkland, 1998), and when policy action does occur it may be limited in scope. Swanson et al. (2010) note several built-in policy adjustments that can be used to contend with both anticipated and unanticipated future conditions. Examples include scheduled reviews of existing policies or review upon a set number of compliance violations. Detection of at risk watersheds or a threshold for drought condition persistence could be used as triggers to review policy effectiveness. Regardless of mechanism, commitment to monitoring, data sharing, and

opportunities for learning are necessary for progress towards adaptation at the state-level.

4. The rulemaking process highlighted the challenges of addressing unique needs between and within stakeholder groups. While the Water Use Reporting Program provides information regarding the spatial and temporal distribution of water use in the state, the relationship between streamflow variability and water needs and values is under-acknowledged. Integration of water users decision-making with streamflow in the form of decision calendars helps identify potential vulnerabilities (e.g. Ricupero, 2009; Kim and Jain, 2010; Lackstrom et al., 2014). While not addressed in this case study, streamflow also is linked to a range of social and cultural values that may often be overlooked in planning processes (e.g. Jackson, 2006; Jackson et al., 2015). While Ch. 587 presented opportunities for stakeholder representation and input, additional research is needed to determine if stakeholder groups are representative of the underlying population (Antunes et al., 2009). Lack of representativeness may lead to undetected vulnerabilities or inappropriate evaluation of trade-offs among objectives. Furthermore, consideration of the time and financial requirements for stakeholders to participate in long-term planning is needed. Increased monitoring will require the engagement of user communities. Reducing barriers to participation and broadening the types of water uses addressed in future in-stream flow processes will be important for ensuring more equitable adaptation processes.

CHAPTER 4
DIVERSITY OF GLOBAL PATTERNS OF PRECIPITATION
VARIABILITY AND CHANGE ON RIVER BASIN SCALES: A
CONDITIONAL QUANTILE APPROACH¹

4.1 Chapter Abstract

Comprehensive characterization of diversity in global patterns of precipitation variability and change is an important starting point for climate adaptation and resilience assessments. Capturing the nature of precipitation probability distribution functions (PDF) is critical for assessing variability and change. Conventional linear regression-based analyses assume that slope coefficients for the wet and dry tails in the PDF are consonant with the conditional mean trend. This assumption is not always borne out in the analyses of historical records. Given the relationship between sea surface temperature (SST) and precipitation, recent trends in global SST complicate interpretations of precipitation variability and risk. In this study, changes in the PDF of annual precipitation (1951-2011) at the global river basin scale were analyzed using quantile regression (QR). QR is a flexible approach allowing for the assessment of precipitation variability and conditioned on the leading empirical orthogonal function (EOF) patterns of global SST that reflect El Niño-Southern Oscillation and Atlantic Multi-decadal Oscillation. To this end, the framework presented a) offers a characterization of the entire PDF and its sensitivity to the leading modes of SST variability, b) captures a range of responses in the PDF including asymmetries, c) highlights regions likely to experience higher risks of precipitation excesses and deficits and inter-annual variability, and d) offers an approach for quantifying risk across specified quantiles. Results show asymmetric responses in the PDF in all regions of

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the world, either in single or both tails. In one instance, QR detects a differential response to the leading patterns of SST in the Tana basin in eastern Africa, highlighting changes in variability as well as risk.

4.2 Introduction

Precipitation is a primary component of the freshwater budget across various spatial and temporal scales. Numerous human and environmental systems such as agriculture, industry, and recreation are sensitively linked to precipitation variability. Furthermore, freshwater-reliant ecosystems provide a range of services such as resource provision, nutrient cycling, water purification, flood protection, and have cultural importance (Brauman et al., 2007; Chang and Bonnette, 2016). In the multifarious contexts noted above, estimation of likelihood of precipitation excesses and deficits over decision-specific thresholds is of interest. This includes characterization of precipitation functional-forms from which PDF parameters are modeled, including changes in central tendency, and position of upper and lower tails which are critical to assessing variability.

Changing patterns of precipitation and its extremes at regional (Bradley et al., 1987; Groisman and Easterling, 1994) and global (Jones, 1988; Diaz et al., 1989; Karl et al., 1995) scales have been documented, with changes in precipitation trends linked with sea-surface temperature (SST) variability studied extensively. El Niño Southern Oscillation (ENSO) is most influential in determining global precipitation variability (Gershunov and Barnett, 1998; Dai and Wigley, 2000; Kenyon and Hegerl, 2010; Sun et al., 2015). However, there are additional patterns of ocean-atmospheric variability with regional effects such as the North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and the Atlantic Multi-decadal Oscillation (AMO) (Scaife et al., 2008; Nigam et al., 2011; Whan and Zwiers, 2017), which are associated with global-scale precipitation changes with regional effects over the United States, Africa, India, and Europe (Enfield et al., 2001; Sutton and Hodson, 2005; Knight et al., 2006).

Given the sensitivities of the precipitation PDF to SSTs, the nature of SST oscillations and combined influence of patterns complicates assessments of precipitation variability. The SST patterns often exhibit slow variations and persist on seasonal to annual time scales. For example, ENSO oscillates between cold and warm phases on a 3-7 year time scale (Deser et al., 2010) while AMO is characterized by slow variations over a 65-80 year period (Enfield et al., 2001). The effect of SSTs on the functional form of precipitation can be to minimize or amplify sensitivities, with persistence of pattern phases implying that locations with significant sensitivities to SST patterns may experience impacts with increased frequency.

Despite these recorded relationships, widely used linear statistical techniques such as linear regression (LR), rely on measures of central tendency and constant variance, assuming that changes in the mean characterize location changes over the entire distribution. Precipitation distributions often violate these assumptions, and changes in the mean often do not characterize changes in extremes (Kim and Jain, 2011; Lee et al., 2013). An example of such an application is Observations: Surface and Atmospheric Climate Change (Trenberth et al., 2007) in the Intergovernmental Panel on Climate Change (IPCC) Climate Change 2007 Working Group I Report. Figure 3.13 on pg. 256 of the report (<https://www.ipcc.ch/report/ar4/wg1/>) assesses mean annual precipitation trends, implying that the risk of a high or low annual total is proportionally increasing or decreasing with the mean and that the variance is time-invariant. Furthermore, with precipitation having a significant relationship with other drivers such as SST, specifying year as the only covariate may not adequately characterize the distributional changes in annual total precipitation, underscoring the need for more flexible approaches.

This work reappraises the nature and type of changes in the magnitude of annual precipitation on the river basin scale. Climate risks are characterized as the changes in likelihood of precipitation excesses and deficits, requiring particular assessment of shifts in the extrema of the precipitation PDF. Unless otherwise noted, in this study risk signifies

changes in likelihood. The PDF aids computation of exceedance and non-exceedance probabilities for a given precipitation threshold. The selection of thresholds may depend upon either a) a specification of precipitation magnitude when exceeded constitutes an extreme event (e.g. an annual precipitation total exceeding 2 standard deviations above the mean), or b) for a specified exceedance probability (e.g. 1% or 100-year return period) the extreme annual precipitation value consistent with the exceedance probability. For the remainder of this study, extreme wet and dry conditions are defined as large excursions from long-term median estimates based on historical data. Consequently, tail probabilities represent the likelihood of such events. Shifts (changes in location) in the tails of the distribution indicate a higher or lower probability of an extreme annual total. A quantile regression (QR) model (Koenker and Bassett, 1978; Koenker, 2017) is applied as an alternative to LR approaches as it (a) is robust to outliers, (b) does not make distributional assumptions, (c) characterizes a variety of shifts across the entire distribution (including extremes), (d) can be used to quantify changes for any specified thresholds (quantile) of interest for coupled human-environmental contexts, and (e) offers insight into exposure and consequence via derivation of spatial patterns of global precipitation sensitivity and changing likelihood induced by SST conditions. In this work, global patterns of conditional quantile response are estimated, with attention to changes in risk. Salient questions addressed in this study are:

1. Based on a quantile regression approach, what are the linkages between river basin scale precipitation and coherent patterns of global sea surface temperature variability?
2. At regional and global scales, what are the detailed spatial characteristics of precipitation variability for lower, median, and upper quantile levels?
3. In what ways can a quantile regression approach be used to estimate the influence of climate variability patterns on conditional risk likelihoods for precipitation?

The rest of this chapter is organized as follows. Firstly, linkages between precipitation and climate variability are delineated (Section 4.3.1) followed by an examination of the advantages of a quantile regression approach over ordinary least squares regression for characterizing distributional asymmetries (Sections 4.3.2-4.3.4). Next, an assessment of the linkages between annual precipitation and the coherent patterns of climate variability at the basin scale globally and regionally is presented (Sections 4.4.1-4.4.3). Lastly, the use of SST variability patterns for estimating conditional risk likelihoods is explored (Section. 4.4.4).

4.3 Data and Methods

4.3.1 Data and Study Region

Annual precipitation for 405 river basins around the world were analyzed (Figure D.1) for the 1951-2011 time period on a June-May annual year. A June-May annual designation captures the expression of El Niño and La Niña events as well as preserves the primary wet season for most basins (Figure D.2). The river basin delineations used for precipitation analysis are from the 405 Major Water Basins of the World dataset obtained from the Global Runoff Data Centre (Global Runoff Data Centre (GRDC), 2007). Global gridded monthly total precipitation dataset at a $0.5^\circ \times 0.5^\circ$ resolution (CRU TS3.22) was obtained from the UK Natural Environment Resource Council's British Atmospheric Data Centre (NERC-BADC), and were produced by the University of East Anglia Climatic Research Unit (Harris et al., 2014). Sea surface temperature (SST) data monthly grids were obtained from National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature V3b dataset with $2.0^\circ \times 2.0^\circ$ resolution (Smith et al., 2008).

Monthly precipitation data was aggregated to produce annual totals, and were areally averaged over the global river basins. Monthly SST data were aggregated at each grid point to produce an annually-resolved dataset, and the long-term trend was removed. To derive the leading SST patterns, Empirical Orthogonal Functions (EOFs) were produced from the detrended data. A correlation matrix was used over a covariance matrix as large variance

differences between elements can lead to a few elements dominating the first few patterns (Jolliffe, 2002). To assess the relationship between the leadings patterns of SST and precipitation variability, precipitation EOFs were produced in a similar manner. Additional details can be found in Appendix E.

4.3.2 Annual Precipitation Variability and Change: Conditional Quantile Functions

Quantile regression (QR) is a robust approach to characterizing changes across the range of precipitation thresholds, including the upper and lower tails. Unlike LR, QR captures responses in upper and lower quantiles that may differ in magnitude and/or direction to the mean, with different implications for variability and risk. Additional details of the methodology and advantages over LR are offered in Koenker (2005). The linear quantile regression model has the form:

$$y_i = \beta_0^{(\tau)} + \beta_1^{(\tau)} x_i + \epsilon_1^{(\tau)} \quad (4.1)$$

where $\beta_0^{(\tau)}$ is the intercept and $\beta_1^{(\tau)}$ is the slope coefficient for the selected quantile τ , which ranges from 0 to 1. The reader should note that τ is not read as an exponent. In this approach, QR allows conditional estimates of precipitation levels (at quantile τ) that are larger than τ and smaller than $(1 - \tau)$ proportion of historical data. In this study, a no-cross restriction is placed on quantile coefficient values for each covariate, as the crossing of quantile regression lines provides erroneous results (Bondell et al., 2010). To assess significance, a permutation test is conducted, where y_i is sampled with replacement and β_i is calculated ($n = 1000$) producing a distribution of coefficient values. A percentile test (0.95, 0.05) is used to determine if β_i is significant. In an effort to characterize the relative sensitivity of basin-scale precipitation to leading patterns of SST variability, the QR approach is used due to its ability to clarify the quantile-by-quantile conditional relationship. To this end, prior to introducing SST covariates (Section 4.4.1), several

illustrative cases were chosen to aid a clearer interpretation of quantile regression coefficients (both their magnitude and signs) across select quantiles.

4.3.3 Distributional Characterization of Synthetic Data

To demonstrate the diversity of responses captured in the QR approach, synthetic precipitation data were generated to mimic geophysical records of the same length as the historical data. The synthetic data exhibit the combinations of upper ($\tau = 0.8$) and lower ($\tau = 0.2$) tail trends; some or all of these may be found in historical records. QR was conducted on the datasets across the quantiles, $\tau = 0.2, 0.5$ (median), and 0.8 , conditioned on time only, and compared to LR results. Figure 4.1*a, e, and i* represent the changes implied by LR, where the entire PDF symmetrically shifts location to a higher or lower magnitude, or undergoes no significant change. However, in both *a* and *i*, changes in $\tau = 0.2$ and 0.8 are asymmetric, indicating differences in distributional probabilities in contrast to LR. *d* is an example where there is only an increase in the position of $\tau = 0.8$. This implies both increased variability, and probability of wet extremes. *b, f, and h* also exhibit single-tailed changes with *b* and *f* showing decreases in variability, while *h* indicates an increased risk of a dry year and increased variability. Similarly, *g (c)* indicates an increase (decrease) in variability due to diverging trends in the tails where LR would find no significant change. Taken together, the diversity of changes discussed above underscore: a) the fidelity with which the QR approach can be applied across cases of variability and change, b) the ease with which one or more covariates (for example, time, ocean-atmospheric indices) can be incorporated, and c) that QR can be readily tailored to be specific to the requisite quantiles or thresholds (including extremas—lower and upper tails) for place-based precipitation variability and change assessments. Additionally, over the range of quantiles, QR-derived regression coefficients constitute the basis to derive conditional probability distribution at a particular value of the climatic covariate (for

example, El Niño conditions). Non-parametric estimation of conditional PDFs and their utility for risk analysis are discussed next.

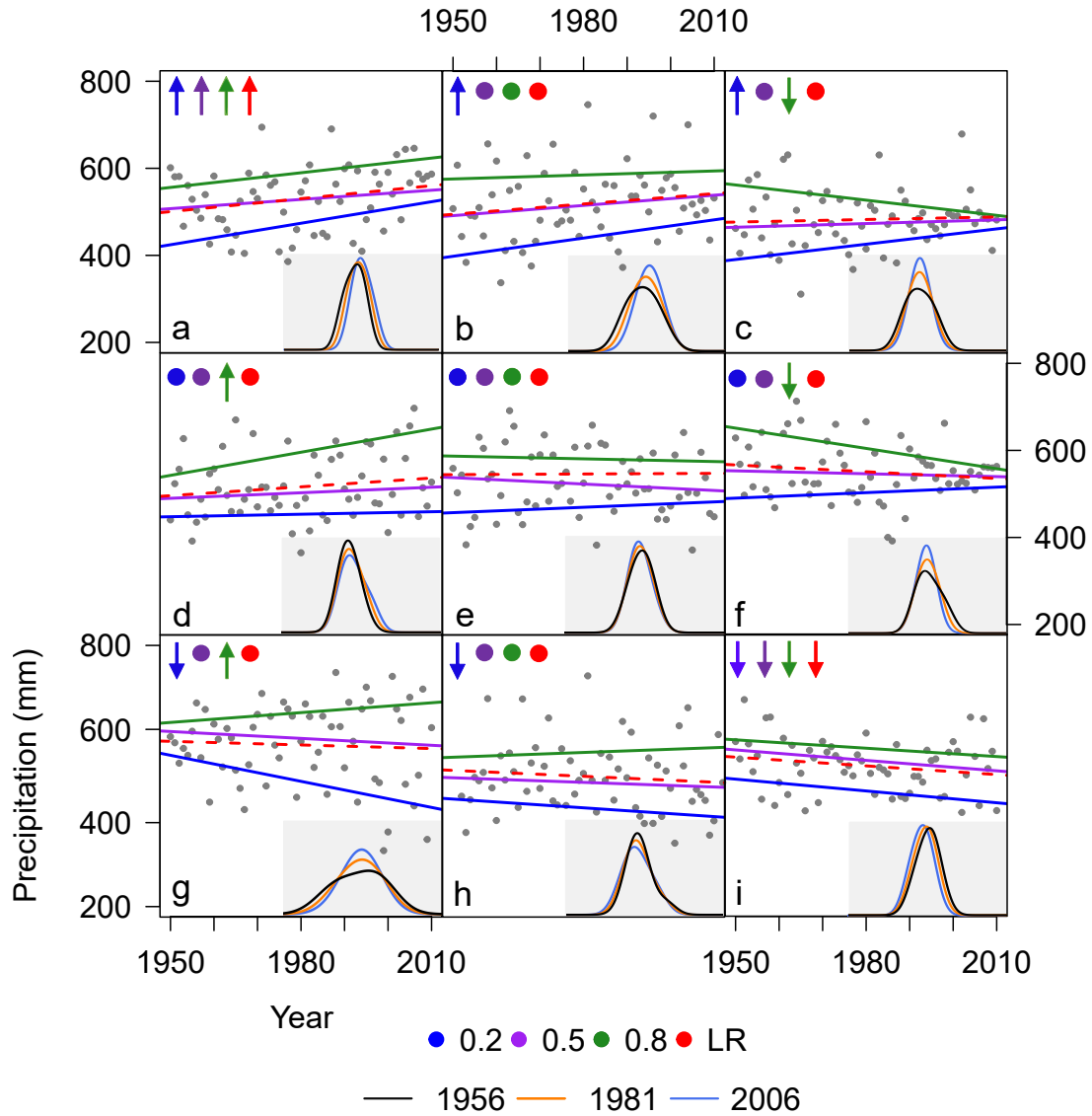


Figure 4.1: Quantile regression of synthetic precipitation data(mm) conditioned on time ($\tau = 0.2, 0.5, 0.8$) highlights the diversity of changes in environmental data. Dashed line shows mean trend estimate. Arrows are coded to represent the direction of change for the respective quantiles at $\alpha = 0.1$. Circles indicate no significant response. Shaded gray areas show empirical probability distributions constructed for years 1956, 1981, 2006.

4.3.4 Changing Perspectives of Conditional Risk

In addition to characterizing the variety of possible quantile responses, conditional empirical probability distributions for each synthetic dataset were constructed for three

different years to highlight differences in exceedance probabilities in the QR approach compared to LR (Figure 4.1). Particularly when there is no significant change in the conditional mean, the results from the LR approach indicate no appreciable change across the entire range of quantiles. For environmental data, this can be restrictive and may lead to mischaracterization of trends under an LR approach. The QR approach allows for semi-independent shifts across quantiles implying changes in the risk of extremes in one or both tails of the probability distribution. For example, Figure 4.1a shows an increase in $\tau = 0.2$ and decrease in $\tau = 0.8$ implying a decrease in variability over time. QR captures a decrease in $\tau = 0.8$ exceedance probability between 1956 and 2006, while a LR approach indicates an increase. A full example comparing the QR and LR exceedance probability differences over time for Figure 4.1c can be found in Appendix D (Figure D.4; Table D.2). While the reader should note that these PDFs are for illustrative purposes only, the QR approach shows that asymmetric changes in exceedance probability with increases (decreases) in upper threshold risk are not necessarily accompanied by proportional decreases (increases) in risk in corresponding lower thresholds.

4.3.5 Basin-Scale Distributional Changes

For a global analysis, the effects of SST variability on annual precipitation for the years 1951-2011 in the 405 global major river basins are assessed across the $\tau = 0.2, 0.5, 0.8$ quantiles using QR. Three covariates are used: year (1951-2011), and the SST time-series for the EOF analysis (EOF1, EOF2). All covariates are uncorrelated. The year covariate values were standardized and centered on 0, minimizing erroneous intercept calculations that may arise when using a wide range of values (Koenker, 2005). Significance of each coefficient was determined at a $p \leq 0.1$ significance level (see Section 4.3.2 for details). A cautionary note to the reader is that trends in annual totals may not be indicative of the precipitation - SST relationship on monthly, seasonal, and episodic timescales.

4.4 Results

4.4.1 SST-Precipitation Relationships

Sea-surface temperature has been shown to significantly correlate with precipitation globally (Diaz and Markgraf, 2000). EOF results show that SST EOF1 and EOF2 explain 33.1% and 10.8% of the variance respectively (Table D.1). SST EOF1 shows the highest anomalies in the Eastern Pacific (Figure 4.2b) with SST EOF2 showing contrasting patterns in the north and mid-Atlantic and the northwestern Pacific to ones in the mid-latitude Pacific (Figure 4.2e). SST EOF1 has a correlation coefficient of $r = 0.93$ with the Niño-3.4 index, which is consistent with studies identifying EOF1 as capturing ENSO phenomenon (Deser et al., 2010; Messié and Chavez, 2011), and $r = 0.72$ with the PDO index. EOF2 has a correlation coefficient of $r = 0.85$ with the Atlantic Multi-decadal Oscillation (AMO) index and $r = -0.3$ with the PDO index. Precipitation EOF1 and EOF2 explain 15.4% and 5.3% of the variability (Table D.1) with EOF1 showing highest correlations in North and South America, Indonesia, and North Australia (Figure 4.2a) and EOF2 with high correlations in sub-Saharan Africa, Northern Europe, and Australia (Figure 4.2d). Comparison of the EOFs of SST and precipitation show high correlation between the first EOFs ($r = 0.92$) with the SST EOFs showing distinct covarying patterns with precipitation (Figure 4.2c). The SST EOF2 and precipitation EOF2 are moderately correlated ($r = 0.4$), but capture sensitivities in Africa which have been linked to AMO (Figure 4.2f). The SST EOF1 and EOF2 time-series are chosen for this study to be used as covariates in a quantile regression analysis model as they explain the highest amount of SST variation, and have the highest correlation to physical modes and precipitation patterns. Additional details can be found in Appendix D.

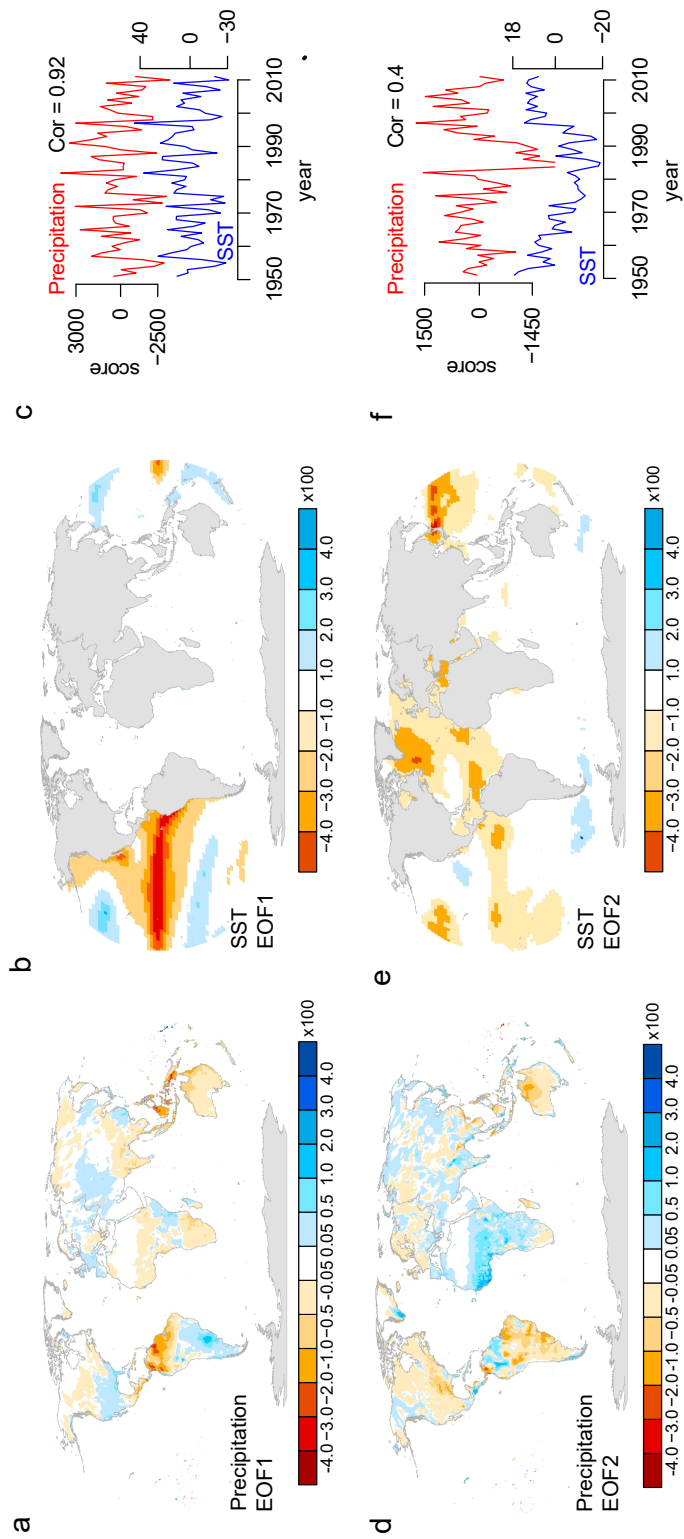


Figure 4.2: Leading statistical patterns of precipitation and sea-surface temperature. a) annual precipitation anomalies over land (June 1951 – May 2011) based on the CRU TS3.22 monthly precipitation grids and b) annual SST anomalies over the global oceans based on NOAA ERSST v3b monthly SST data set (June 1951 – May 2011). c) Comparison of global land precipitation EOF1 and SST EOF1 time-series d) Second precipitation EOF e) Second SST EOF f) Comparison of precipitation EOF2 and SST EOF2. Partial correlation with trend shows no change in correlation coefficients.

4.4.2 Variability in Quantile-Specific SST-Precipitation Relationships

The relationship between SST variability and precipitation for the years 1951-2011 is assessed at $\tau = 0.2, 0.5,$ and 0.8 quantiles in the 405 global major river basins by:

$$\text{Annual Precipitation}(\tau | x) = \beta_0^{(\tau)} + \beta_1^{(\tau)}\text{year} + \beta_2^{(\tau)}\text{EOF1} + \beta_3^{(\tau)}\text{EOF2} + \epsilon^{(\tau)} \quad (4.2)$$

where $0 < \tau < 1$ represents the quantile, year is the time-series 1951-2011, and EOF1 and EOF2 are the respective SST time-series from the analysis of the global SST data. The spatial patterns of precipitation response across quantiles (Figure 4.3) identifies regions that are sensitive to EOF1 and EOF2, depicting the influence of phase and magnitude of SST on annual precipitation distributional response. The same analysis was conducted on annual precipitation data corrected for unequal areal extent of grids across latitudes, with negligible differences (Figure D.5). Coefficient signs and values across quantiles indicate that shifts are in the extremes of the distribution ($\tau = 0.2, 0.8$), and do not coincide with the slope of the estimated conditional mean function. EOF1 shows the most influence on precipitation with 62.0% of all basin area showing a significant response ($p \leq 0.1$) in at least one quantile, followed by EOF2 (44.1%) and trend (35.5%). Findings summarized by covariate include:

1. Precipitation shows significant increases across quantiles over time (trend) in the United States, South America, Africa, and decreases in southern Asia, and western Europe. In particular, both the Mississippi River basin in North America and the Parana Basin in South America show significant increases in all 3 quantiles evaluated.
2. EOF1 produces stronger magnitudes of response relative to the year covariate, with the PDF varying widely in shape and position from year to year. When EOF1 is in positive phase, corresponding to SST patterns in the tropical Pacific consistent with El Niño, there are strong negative responses in northern parts of South America, Africa, Southeast Asia, and Australia. Strong positive responses are seen in southern South America, and some moderate increases in the United States and Europe. For

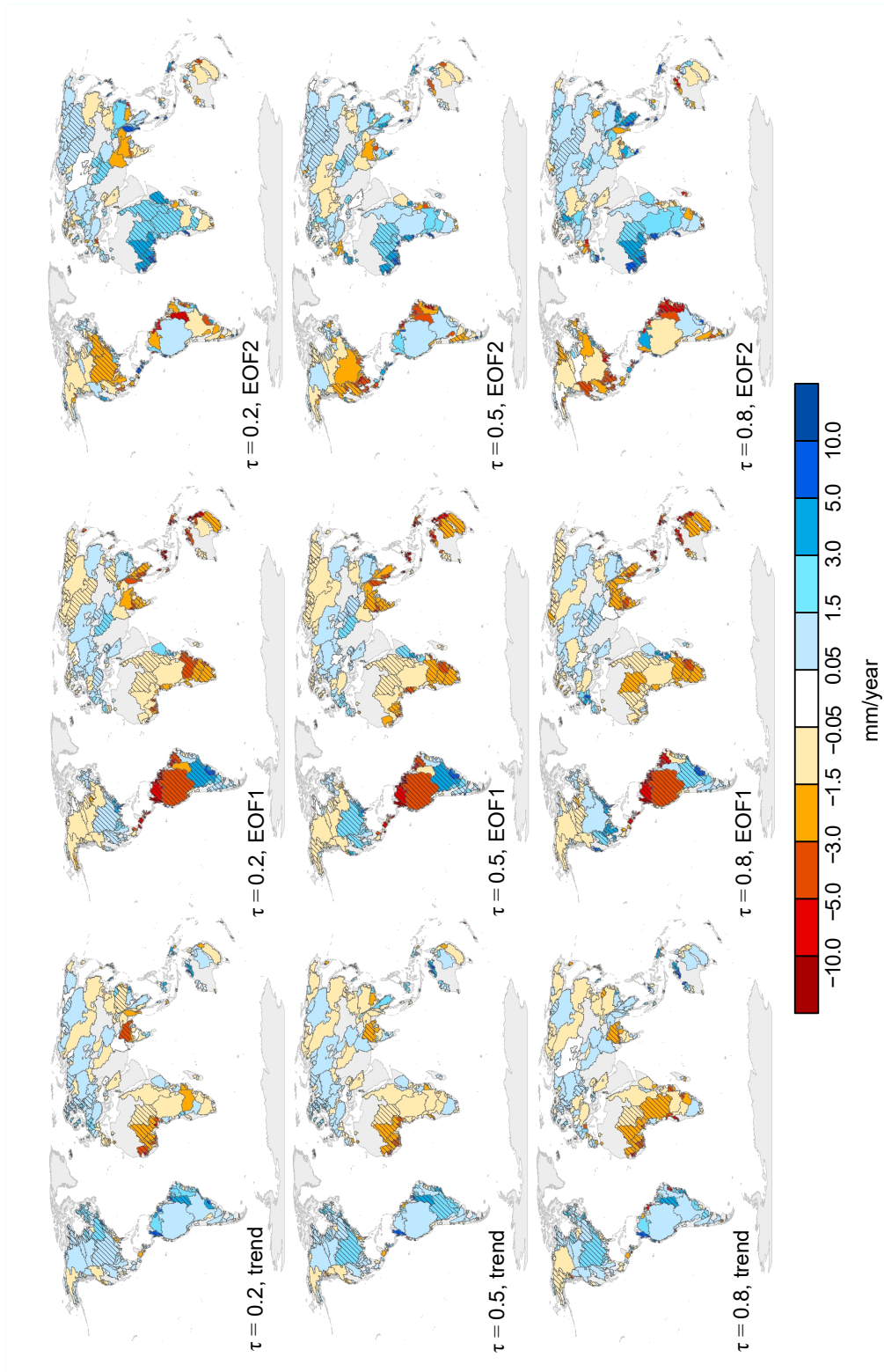


Figure 4.3: Spatial distribution of precipitation trends conditioned on years 1950-2011, EOF1 and EOF2. Trends are evaluated on select quantiles ($\tau = 0.2, 0.5, 0.8$) of basin areal average annual precipitation. Cross-hatch represents significance at $\alpha = 0.1$

example, the Godavari and Ganges basins in the Indian subcontinent show negative responses consistent across quantiles.

3. When EOF2 is in positive phase, corresponding to warm temperatures in the Arctic and north Pacific, negative sensitivities are shown for $\tau = 0.5$ and 0.8 in the western United States, while negative responses in $\tau = 0.2$ are limited to the east. There are also strong to moderate positive responses in Africa, and in Southeast Asia in $\tau = 0.8$ only, while northern latitudes in Asia show only low magnitude positive response. For example, the Yenisei basin shows a positive response of similar magnitude across quantiles, while the Guadalquivir basin in Spain shows a stronger positive response in $\tau = 0.8$ than $\tau = 0.2$ and 0.5 indicating an increase in variability.

With SST predictability, this spatial view highlights the overall sensitivity across quantiles, and the regional patterns of coherent precipitation variability. $\tau = 0.2$ and 0.8 coefficients that differ from each other in magnitude and sign from the median specifically demonstrate the value of the QR model with shifts evident across a range of locations. Wider distributions imply a higher uncertainty in anticipating the amount of precipitation, with implications for planning regarding use in sectors such as agriculture and industry. To this end, a continent-scale examination of upper and lower quantile SST-precipitation sensitivities with discussion of non-climatic factors such as infrastructure, population, and water demand and sectoral uses that may amplify or temper risk can be found in Appendix E.

4.4.3 Combinations of Upper and Lower Precipitation Quantile Responses

To explicitly categorize the diversity of quantile shifts, combinations of significant positive and negative, and non-significant changes in $\tau = 0.2$ and 0.8 , hereafter referred to as typologies, were constructed for each covariate as demonstrated in the synthetic example (Section 4.3.3). These typologies (Figure 4.4) offer a synthesized view of Figure 4.3, allowing for a clearer spatial assessment of regions undergoing similar shifts in response to

covariates. In the following, typologies will be referenced by Figure 4.1*a-i*. Typologies characterized by shifts in single quantiles (*b, d, f, h*) indicate higher variability (increase or decrease) than simultaneous shifts in the same direction. Conditional quantile responses are all for positive EOF1 and EOF2 conditions. Responses in each quantile are opposite in sign for negative EOF1 and EOF2 conditions.

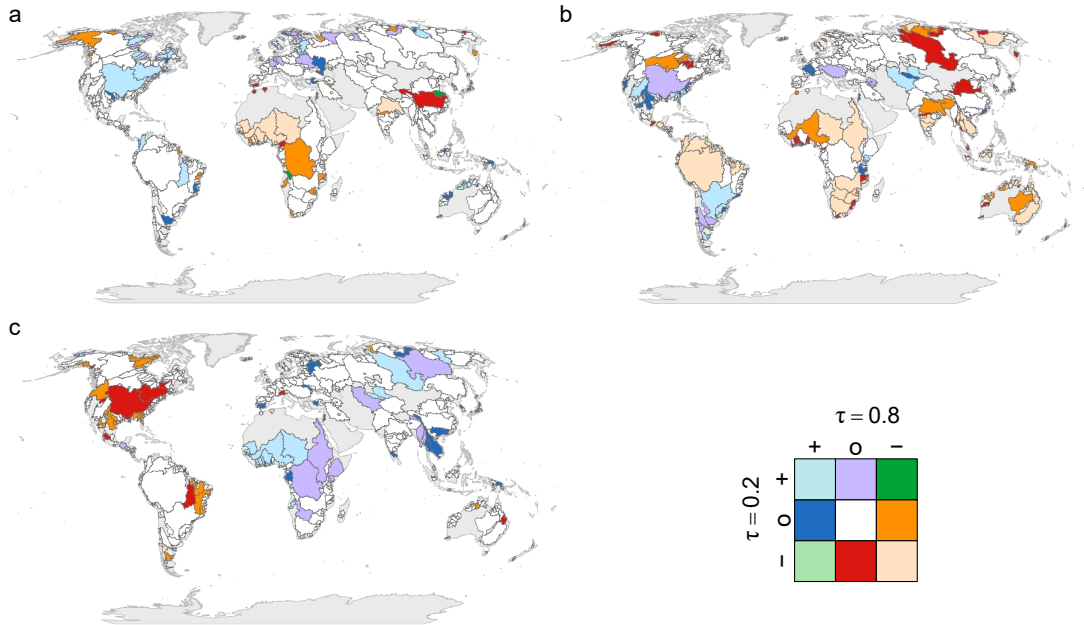


Figure 4.4: Typology of basin-scale precipitation sensitivity to climate variability and change. Typology is based on pairwise combinations of regression coefficients at $\tau = 0.2$ and 0.8 . Basins are color-coded according to combinations of positive (+), negative (-) significant response ($\alpha = 0.1$), and non-significant (o) response. Typologies are shown for annual precipitation totals (mm) for the 1951 —2011 period conditioned on (a) years 1951 —2011, (b) EOF1, and (c) EOF2.

Globally, EOF1 and EOF2 show the most influence on precipitation and trend the least with 56.7%, 41.0% and 31.1% of basin land area showing a response respectively. For trend, basins are largely characterized by either increases or decreases in both $\tau = 0.2$ and 0.8 . (Fig. 4a). While trend captures temporal variability as well as other drivers in the system, the analysis in Section 4.4.2 demonstrated that distributional changes are more sensitive to EOF1 and EOF2, with larger covariate coefficients calculated.

4.4.3.1 Africa

Trend shows no response or decrease in either one or both quantiles suggesting drier conditions. Shifts conditioned on EOF1 generally show decreases except for eastern Africa. Conversely, EOF2 shows increases in quantile position. Key examples include the Pangani basin in Tanzania characterized by typology *a*, indicating increased probability of wet events. The Tana basin is characterized by type *a* under EOF1 and *b* under EOF2 indicating a decrease in probability of dry conditions. Western African basins such as Niger, Lake Chad, and Sassandra, all show increases in both quantiles under EOF2. For EOF1, the Niger basin (*g*) shows a reduction in variability and probability of wet conditions. Lake Chad experiences a decrease in both quantiles. The continent generally experiences precipitation deficits (excesses) under positive EOF1 (EOF2).

4.4.3.2 Australia and Southeast Asia

Basins primarily show precipitation decreases under EOF1. For example, the Blackwood basin is characterized by *h* under EOF1 and *f* under EOF2. Type *h* indicates reduced probability of wet events and lower variability, and *f* an increase in dry events and higher variability. The Murray (*i*), Pahang (*h*) and Kinabatanga (*i*) basins similarly show decreases under for EOF1. Conversely for EOF2, there is no response in either the Kinabatanga or Murray basins and an increase in both quantiles (*a*) in the Pahang basin.

4.4.3.3 Asia

Most basins show precipitation decreases under EOF1 and increases under EOF2. For example, the Mekong shows decreases in both quantiles under EOF1 (*i*) and increase in $\tau = 0.8$ (*d*) under EOF2. Similarly, the Yellow river shows higher probability of dry events (*h*). The Ganges basin shows a decrease in $\tau = 0.8$ under EOF1 indicating a reduction in variability and wet events. Conversely, the Changjiang basin shows an increase in $\tau = 0.8$ indicating an increase in variability and probability of wet events.

4.4.3.4 Western Europe

Few basins show significant response, with general increases under EOF1 and EOF2. For example, the Garonne basin in France shows increase in both quantiles (*a*) under EOF1, while the Rhone and Seine show increases in $\tau = 0.8$ only, indicating greater variability. The Thames shows a decrease in variability under EOF1 with an increase in $\tau = 0.2$ (*b*). The Guadalquivir basin is a key example of response to EOF2, showing an increase in $\tau = 0.8$ (*d*).

4.4.3.5 Eastern Europe and Russia

The basins with highest sensitivity are some of the least populated areas of the Northern Hemisphere. For example, the Yenisei basin shows a decrease in $\tau = 0.2$ under EOF1 (*h*) and an increase in both quantiles for EOF2 (*a*). This indicates a higher variability and probability of dry conditions for EOF1. Neighboring basins show similar results with decreases (increases) in either both or single quantile positions for EOF1 (EOF2) conditions.

4.4.3.6 South America

EOF1 dominates the significant response with deficits in the north and excesses in the south. EOF2 has an influence along the east coast and southern tip, showing decreases in quantile position. For example, the Orinoco and Amazonas basins show decreases in both quantiles (*i*) indicating higher probability of deficits under EOF1. Conversely, the Parana and Uruguay basins show simultaneous increases (*a*). Under EOF2, the Parana basin shows a decrease in $\tau = 0.2$ (*h*).

4.4.3.7 North America

Trend broadly shows increases across the eastern US and Canada and decreases in northwestern Canada. EOF1 shows increases across the US and central America and decreases in Canada, while EOF2 shows decreases. For example, the Sacramento and

Colorado river basins show increases in both quantiles (*a*) and increase in $\tau = 0.8$ (*d*) respectively, showing increased probability of wet events and higher variability. Conversely, the Columbia river basin shows decreases in $\tau = 0.2$ (*f*) under EOF2. In the southeast US, the Alabama & Tombigee and Suwannee basins show increases in both quantiles under EOF1 and decreases in $\tau = 0.8$ under EOF2. In the northeast US, the Penobscot river basin shows a decrease in $\tau = 0.2$ (*h*) under EOF2 suggesting an increase in variability. Typologies indicate the directionality of shifts, imply uncertainties, and highlight which drivers (EOF1 or EOF2) are most critical to these changes. For basins where EOF1 and EOF2 are both significant, distributional shifts are highly dependent on the commingling of covariate conditions. For example, the Tana basin in East Africa shows increases (*a*) when EOF1 is positive, and an asymmetric increase (*b*) when EOF2 is positive. When EOF1 and EOF2 are in the same phase, shifts are amplified depending on the magnitude, while opposite phase tempers the overall response and the directionality of shifts becomes dependent on covariate magnitudes. A related notion is the change in variability and risk implied by various combinations of EOF1, EOF2 conditions.

4.4.4 Assessment of Distributional Variability and Conditional Risk

The quantile-specific coefficients for EOF1 and EOF2 at a given location apportion the influence of each SST to risk. For given coefficients, the phase and magnitude of EOF1 and EOF2 determine the distribution of precipitation in a location, and thereby the risk likelihood at specified thresholds. To illustrate how EOF1 and EOF2 conditions jointly influence shifts in aspects of the precipitation distribution, quantile responses were calculated for the range of possible EOF combinations. This was applied to $\tau = 0.2, 0.5, 0.8$, and for the $\tau = 0.8 - 0.2$ quantile range illustrating shifts in location and distributional spread (variability). A case example for the Chad River basin in Northern Africa is presented (Figure 4.5), with $\tau = 0.2, 0.5, 0.8$ significant to EOF1 and EOF2. The slopes of the contours indicate higher precipitation sensitivity to EOF2 in $\tau = 0.2$, and to EOF1 for

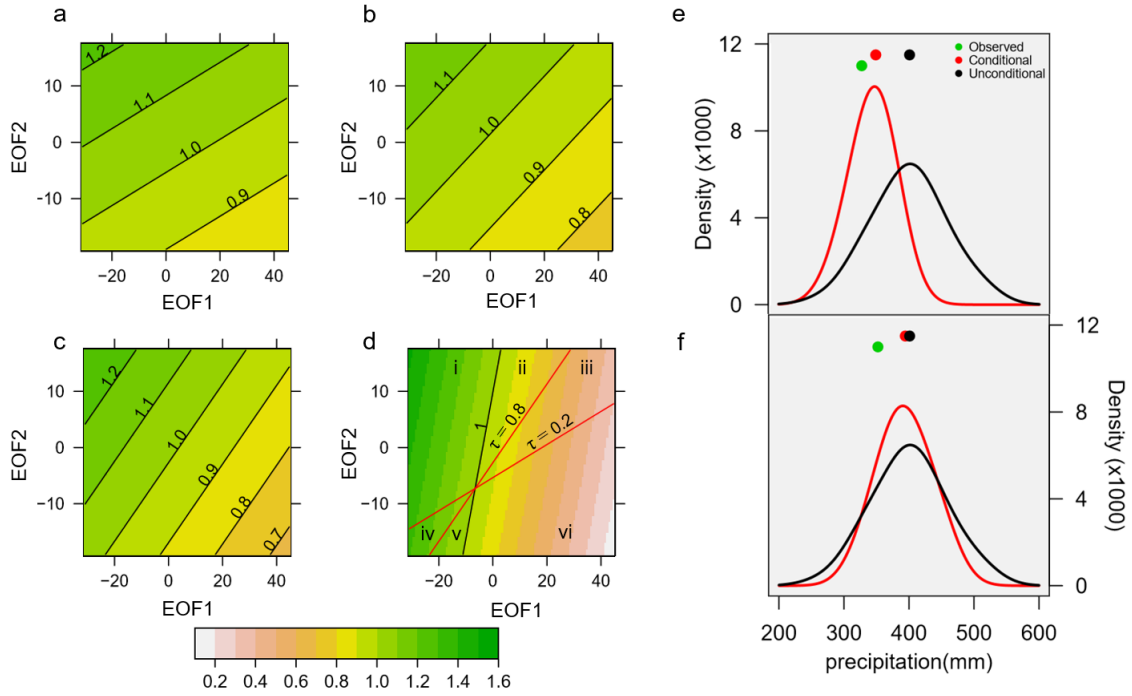


Figure 4.5: Precipitation quantile position changes for possible EOF1, EOF2 values in the Chad River Basin, Africa. Ratio of conditional quantile regression coefficients of precipitation to unconditional quantiles at a) $\tau = 0.2$, b) $\tau = 0.5$, c) $\tau = 0.8$. Ratios > 1 indicate an increase in exceedance probability compared to the unconditional quantile, and ratios < 1 signify a decrease. d) Classification of changes in magnitude and direction of $\tau = 0.2, 0.8$. Each red line marks the EOF1, EOF2 pairs for which conditional and unconditional τ are equal. Areas numbered (i-vi) show possible combinations of $\tau = 0.2, 0.8$ responses with implied changes for variability and risk (Table 4.1). A comparison of unconditional and conditional PDFs during distinct tropical Pacific sea surface temperature conditions: e) Strong El Niño event (1982-1983) and f) median conditions (1990-1991). For significant departures in EOF1 and EOF2 median conditions, the precipitation distribution undergoes wide excursions from the unconditional state.

$\tau = 0.8$ and the $\tau = 0.8 - 0.2$ quantile range. Distributional changes are characterized by 6 bounded areas depending on covariate phase and magnitude (Figure 4.5d; Table 4.1). For any global SST condition, represented as a pair of EOF1 and EOF2 values, the appropriately conditioned precipitation conditional distribution can be determined for any basin.

Table 4.1: Conditional Quantile Response for the Chad River Basin

Region	$\frac{P_\tau(EOF1,EOF2)}{P_\tau}$		$\frac{P_{0.8}(EOF1,EOF2)-P_{0.2}(EOF1,EOF2)}{P_{0.8}-P_{0.2}}$	Risk	
	$\tau = 0.2$	$\tau = 0.8$		$\tau = 0.2$	$\tau = 0.8$
	i	↑	↑	↑	↓
ii	↑	↑	↓	↓	↑
iii	↑	↓	↓	↓	↓
iv	↓	↑	↑	↑	↑
v	↓	↓	↑	↑	↓
vi	↓	↓	↓	↑	↓

For example, unconditional and conditional PDFs using EOF1 and EOF2 as covariates were constructed for 1982-1983 and 1990-1991. In the late 1970s, stronger ENSO amplitude was observed, with 1982-1983 being one of the most extreme El Niño events of the examined record. In a linear QR context with statistically significant regression slopes, significant departures from the median state of the covariate values can produce dramatic shifts in the conditional PDF. For the 1982-1983 event, EOF1 = 37.24 and EOF2 = -5.06. This event falls in region vi of Figure 4.5d, which for this basin is characterized by a decrease in variability, a decrease in risk of extreme wet conditions, and an increase in risk of extreme dry conditions (Table 4.1). The conditional distribution acknowledges that the probability of the precipitation total for 1982-1983 occurring is greater than in the unconditional distribution. Conversely, the 1990-1991 year is characterized by EOF1 and EOF2 conditions that do not depart significantly from the long-term median (EOF1= 4.15; EOF2= -1.39). Due to the small values, the quantile shifts are minimal (Figure 4.5f). The observed value falls within the middle 60% of both distributions, with each representing a similar exceedance probability for the observed total. In the absence of EOF1 and EOF2 information, the unconditional distribution may over- or underestimate the likelihood of exceeding given thresholds for years with significant departures from mean conditions.

4.5 Summary and Conclusions

The analysis presented considers the changes of the annual precipitation distribution conditioned on leading patterns of global SST variability for 405 major river basins. The results show that (a) sensitivities to EOF1 and EOF2 conditions vary across quantiles resulting in asymmetric shifts with implications for uncertainty and changes in exceedance probabilities, and (b) when EOF1 and EOF2 conditions depart significantly from median states, stationary distributional approaches systematically over and underestimate risk.

1. Given that the leading patterns of SST variability are strongly correlated with global precipitation patterns, apportioning variability from trend to SST-based covariates and stratifying variation across quantiles affords a clearer understanding of the variability in annual precipitation. Results show widespread sensitivities to EOF1, particularly in South America, Africa, the United States, and Southeast Asia. Fewer basins are sensitive to EOF2, with responses in parts of Africa, Southeast Asia, and high northern latitudes. Typologies highlight a range of single-quantile sensitivities to EOF1 and EOF2. For example, EOF1 shows increases in $\tau = 0.2$ in parts of North America with EOF2 showing decreases in $\tau = 0.2$ only. In parts of Africa, Australia, and South America, EOF1 shows decreases in both tails, while EOF2 shows the opposite response in the lower tail only. Asymmetric or single-tail responses indicate both changes in variability and risk.
2. The precipitation conditional PDF is jointly influenced by EOF1 and EOF2. Basins with significant sensitivities in either or both tails – representing large departures from median annual totals – to EOF1 and EOF2 experience a range of changes dependent on phase and magnitude. If EOF1 and EOF2 quantile-specific coefficients are of the same sign, EOF1 and EOF2 produce an additive response when in the same phase, and may minimize response when in different phases. For parts of Africa, positive EOF1 and negative EOF2 events amplify the risk of dry conditions compared

to positive EOF1 and EOF2 events. QR offers an approach for assessing the SST-influenced changes across a range of quantiles, which can be applied at various spatial and temporal scales.

3. Precipitation is a primary component of water resources assessment – Mischaracterization of tail-specific changes and variability has the potential of compounding error and can lead to shortcomings in assessment of risk and uncertainty. For example, Dai (2012) assessed global-warming induced drought and found widespread increase in drought risk, with many regions influenced by ENSO-induced precipitation changes. However, the results presented here show that responses in the tails to SST variability do not necessarily correspond to the mean, indicating that drought risk can be further amplified or reduced due to changes in annual total precipitation. Likewise, there are similar implications for water supply (García-García and Ummenhofer, 2015; Richey et al., 2015).
4. Quantile regression is a robust method of estimating the annual precipitation distribution. QR a) allows quantiles to move semi-independently of each other, b) is robust to outliers, and(c) offers a more explicit characterization of variability and implied risk. LR methods assess mean shifts but mischaracterizes changes in the upper and lower quantiles. The QR model highlights sensitivities of distinct parts of the annual precipitation distribution to SST with implications for changes in risk for precipitation excesses and deficits.

In closing, it is noted that the analysis presented imposes a restriction of a linear model. A linear model assumes that precipitation has equal and opposite responses to positive and negative EOF1 and EOF2 phases; some deviations have been noted in a recent study (Cai et al., 2011). Furthermore, while the empirically-derived patterns are uncorrelated there have been studies that show AMO modulates the amplitude of ENSO events in some regions (Power et al., 1999; Kayano and Capistrano, 2014). The

QR methodology and analyses presented here can be conducted for any functional form that is suited to data for a given scale and sectoral context. Assessment of precipitation at other spatial and temporal scales in the future is valuable to assessing more regional or local sensitivities to climate variables for consideration in other analyses and decision-making.

CHAPTER 5

OVERLOOKED TRENDS IN GLOBAL ANNUAL PRECIPITATION REVEAL UNDERESTIMATED RISKS²

5.1 Chapter Abstract

Numerous human and environmental systems are sensitive to the spatial and temporal distribution of precipitation, including agriculture, water supply, and ecosystems. Trends in observed precipitation form an important line of evidence to understand how changes may increase system vulnerabilities. Linear trends reported in US and global climate assessments reflect changes in mean annual precipitation. Mean trends may not reflect changes across other quantiles in the precipitation probability distribution, including the tails (very high and low precipitation levels), leading to systematic mischaracterization of climate risk. In this study, global annual precipitation is reanalyzed using quantile regression to reveal overlooked trends. Trends in the tails are inconsistent with the mean in 44.4% of land area and 40.7% of rainfed agricultural regions. Previously undetected trends offer a more accurate view of the changing climate. This work enables reappraisals of risk aggregated over thresholds in human and environmental systems, enabling reevaluation of threats and identification of appropriate adaptation strategies.

5.2 Introduction

Precipitation is the primary driver of freshwater availability. Portraits of estimated and projected climatic change routinely drive public policy conversations regarding global change and impacts, with precipitation being one of the most prominent variables considered (Millennium Ecosystem Assessment, 2005; Bierbaum et al., 2014). Numerous

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systems such as agriculture (Hatfield. et al., 2014; Moore and Lobell, 2015), energy systems (Carvajal et al., 2017), water supply (Vörösmarty et al., 2000), ecosystems(Grimm and Tedeschi, 2009), and disease epidemics (Nyakarahuka et al., 2017), show sensitive dependence to precipitation. For example, more than one billion people rely on agriculture as their primary source of livelihood, with over two-thirds of the population of Sub-Saharan Africa involved in agriculture-related activities (Corvalan et al., 2005). When precipitation exceeds thresholds (Guntenspergen, 2014) important to human and environmental systems, both from inter-annual variability and multi-year extremes, the risk of experiencing detrimental impacts increases. Long-term and episodic precipitation excesses and deficits at crop-specific thresholds have been shown to reduce yields (Cane et al., 1994; Hatfield. et al., 2014) and can have significant economic impacts. In one instance, the 2012 US drought event had estimated losses totaling \$32.4 billion, largely in the agricultural sector due to low precipitation and high evaporation rates (NOAA NCEI, 2018). Changes at one ecologically important threshold can result in a range of interrelated impacts to the system. For example, maintaining forest moisture above biophysical thresholds minimizes system vulnerability to forest fires, disease, and other disturbances that can lead to downstream impacts to populations (Jaeger et al., 2013). Trends at precipitation thresholds for these various contexts may also depart from mean trends, further underscoring the need for flexible approaches to characterize precipitation variability and change

5.3 Trend Assessment Over the Entire Range of Variability

Historical annual and seasonal trends of precipitation have been extensively studied at regional and global scales (Karl et al., 1995; Jones, 2001; Nickl et al., 2010; Becker et al., 2013; Gu and Adler, 2015), as have comparisons with reanalysis data (Ren et al., 2013; Gu and Adler, 2018) and projections under future conditions (Trenberth et al., 2007; Lintner et al., 2012). The historical record of annual precipitation can be summarized by the probability distribution function (PDF), where the frequency with which precipitation

amounts within a certain interval occur and the probability of exceedance (non-exceedance) above (below) a given threshold can be readily estimated. Regression analyses of historical precipitation allow assessments of PDFs over time that aid assessment of: a) threshold exceedances and b) impacts across precipitation-sensitive systems. U. S. (Walsh et al., 2014) and global climate assessments (Trenberth et al., 2007) have reported annual trends derived from linear regression-based (LR) methods, constituting a baseline for understanding changes in climate risk. However, LR assumes a PDF location-shift model where a) trends are expressed as changes in mean, thus causing the entire PDF to shift and b) variance remains unchanged. Therefore, LR assesses for symmetric changes in precipitation, assuming that increased probability of high (low) annual totals must coincide with a decreased probability of low (high) annual totals. To this end, quantile regression (QR) (Koenker and Hallock, 2001) is used to assess overlooked trends in annual total precipitation and overcomes the limits imposed by LR as it a) comprehensively quantifies trends across all thresholds of the PDF, where quantile τ corresponds to the precipitation level at which τ proportion of the historical data is exceeded, b) does not make distributional assumptions, and c) estimates responses at each τ locally, allowing for asymmetric responses across the distribution (see 4 for more details). While non-parametric methods are flexible, they are limited in their ability to characterize the entire PDF. Previous studies have assessed historical trends in annual-scale extremes (Karl et al., 1995; Groisman et al., 2005; Westra et al., 2013). Trends in these extremes are not necessarily equivalent to the trend in annual totals, leading to a mischaracterization of annual trends. Annual trends accentuate or minimize the impacts of episodic extremes (Sukhatme and Venugopal, 2016); a reappraisal of annual trends at select thresholds can offer improved understanding of inter-annual precipitation variability and risk. In this chapter annual total precipitation at the global scale is reanalyzed using QR to reveal trends that are overlooked by LR approaches in terms of spatial extent, regionality, and

severity. Identification of areas where these overlooked trends correspond with population and areas of rainfed agriculture underscore the implications of trend mischaracterization.

5.4 Data and Methods

5.4.1 Data Selection and Processing

Monthly mean precipitation grids at $1^\circ \times 1^\circ$ resolution from June 1950-May 2017 are used for this study (NOAA ESRL PSD, 2017). Grids were aggregated on a June to May annual year to better preserve a) monsoonal precipitation and b) ENSO - driven precipitation on an annual scale. For example, the designation of 1950 is defined by June 1950 -May 1951. The aggregated monthly mean precipitation grids were multiplied by $365.25/12$ to produce the annual total precipitation at each grid cell. To ensure commensurability in the mean trends, LR was conducted for the 1950 - 2016 period for both June - May and January - December annual year designations (Figure F.1). Slope coefficients for the two annual year designations have a correlation of $r = 0.99$ on the global scale.

Population data was obtained from the 2015 UN-adjusted population count v4 dataset at a 1km resolution. Rainfed agriculture land types were extracted from the Anthropogenic Biomes of the World v1. Data is at a 10 km resolution. Anthropogenic biomes with the descriptor of rainfed types (Rainfed Villages, Rainfed Mosaic Villages, Residential Rainfed Mosaic, and Populated Rainfed Cropland) were chosen as representative of rainfed agriculture land. Descriptions of all land types in the dataset can be found in Ellis and Ramankutty (2008).

5.4.2 Precipitation Data Quality

To account for differences in results arising from the use of alternative gridded precipitation products, confirmatory analysis was pursued. The PREC/L at a $0.5^\circ \times 0.5^\circ$ resolution and CRU TS4.01 monthly precipitation datasets on a June - May annual

year from 1950 - 2011 were compared. The correlation of the annual total time series is high for large areas of the globe (Figure F.2), with low correlation over parts of North and Central Africa, upper northern latitudes, and western South America. Differences in these areas likely arise due to sparse station coverage and differing interpolation processes among the precipitation products. The correlation of global annual mean precipitation between the products is $r = 0.95$, showing high agreement. To ensure that regression results are not biased due to year-to-year persistence in the precipitation data, autocorrelation was applied with significant lag 1 autocorrelation present in only 7.7% of grid cells (Figure F.3).

5.4.3 Trend Calculation with Wild Bootstrap

Trends are assessed through Quantile Regression (QR) using the `quantreg` package for R statistical software. This work uses a linear QR model as:

$$Y(\tau|x) = \beta_0^{(\tau)} + \beta_1^{(\tau)}x + \epsilon^{(\tau)} \quad (5.1)$$

where Y is annual precipitation, τ the quantile such that $0 < \tau < 1$, $\beta_0^{(\tau)}$ is the intercept, $\beta_1^{(\tau)}$ is the slope, x is the time-series 1950 - 2016, and $\epsilon^{(\tau)}$ are the errors. QR allows for the conditional estimation of the precipitation level at quantile τ , such that $(1 - \tau)$ proportion of the historical data is greater than the evaluated precipitation level. A no-cross restriction is placed on the calculation of $\beta_0^{(\tau)}$ and $\beta_1^{(\tau)}$ such that the regression lines calculated at each quantile do not intersect, which would produce physically indefensible results. The time series 1950 - 2016 is standardized and centered on 0 prior to data fitting, as large ranges of covariate values can lead to erroneous intercept calculations. Trends are assessed at the median ($\tau = 0.5$) as a robust measure of central tendency, as it is insensitive to outliers, and at $\tau = 0.2$ and 0.8 representing the dry and wet tails respectively. Wild bootstrap⁴⁸ is used to measure significance as it accounts for heteroscedasticity in the residuals. Residuals are resampled, weighted, and the fit recalculated $n = 1000$ times with a significance level of $\alpha = 0.05$. Residuals at each grid point are sampled in the same order to minimize differences between neighboring cells.

5.4.4 Trend Typology

To capture the diversity of changes in the tails of the precipitation probability distribution function, pairwise combinations of positive and negative significant, and non-significant slope coefficients for $\beta_1^{(\tau)}$ and $\beta_2^{(\tau)}$ are evaluated for $\tau = 0.2$ and 0.8 . There are 9 unique combinations of positive and negative changes between the upper and lower quantile where the response for at least one quantile is significant. Typology elements where the response in only one quantile is significant implies changes in variability. To assess how overlooked trends coincide with population, the typology was first resampled to a 1 km resolution and population grids were aggregated by type using ArcGIS 10.2. Typology grids were similarly resampled to a 10 km resolution prior to intersection with the rainfed land types to determine the percentage of rainfed area characterized by each typology.

5.5 Global Reassessment of Precipitation Trends at Specified Thresholds

Trends in the median ($\tau = 0.5$; Figure 5.1a) and the dry ($\tau = 0.2$) and wet ($\tau = 0.8$) tails of precipitation PDF (very low and high precipitation levels; Figure 5.2), are used to characterize annual total precipitation variability on the global scale. $\tau = 0.2$ and $\tau = 0.8$ are selected as the representative thresholds for dry and wet tails of the precipitation distribution, respectively. Given the modest sample size, more extreme quantiles ($\tau > 0.8$ and $\tau < 0.2$), while calculable, are associated with high uncertainty (Figure F.3). Trends in LR and $\tau = 0.5$ are consistent in most locations as they are both measures of central tendency, with $\tau = 0.5$ a more robust measure due to its insensitivity to outliers. Considering the location-shift model whereby a significant trend in LR corresponds to a significant trend in the same direction for all quantiles evaluated, the direction and significance of trends in LR and QR are intersected (Figure 5.1a). Three possible patterns are assumed by the location-shift model: LR and all quantiles are consistent in significance and direction of trend (C), only LR and the median are consistent (M), and LR and quantiles are inconsistent (I). There are consistencies in significant trends across LR and all

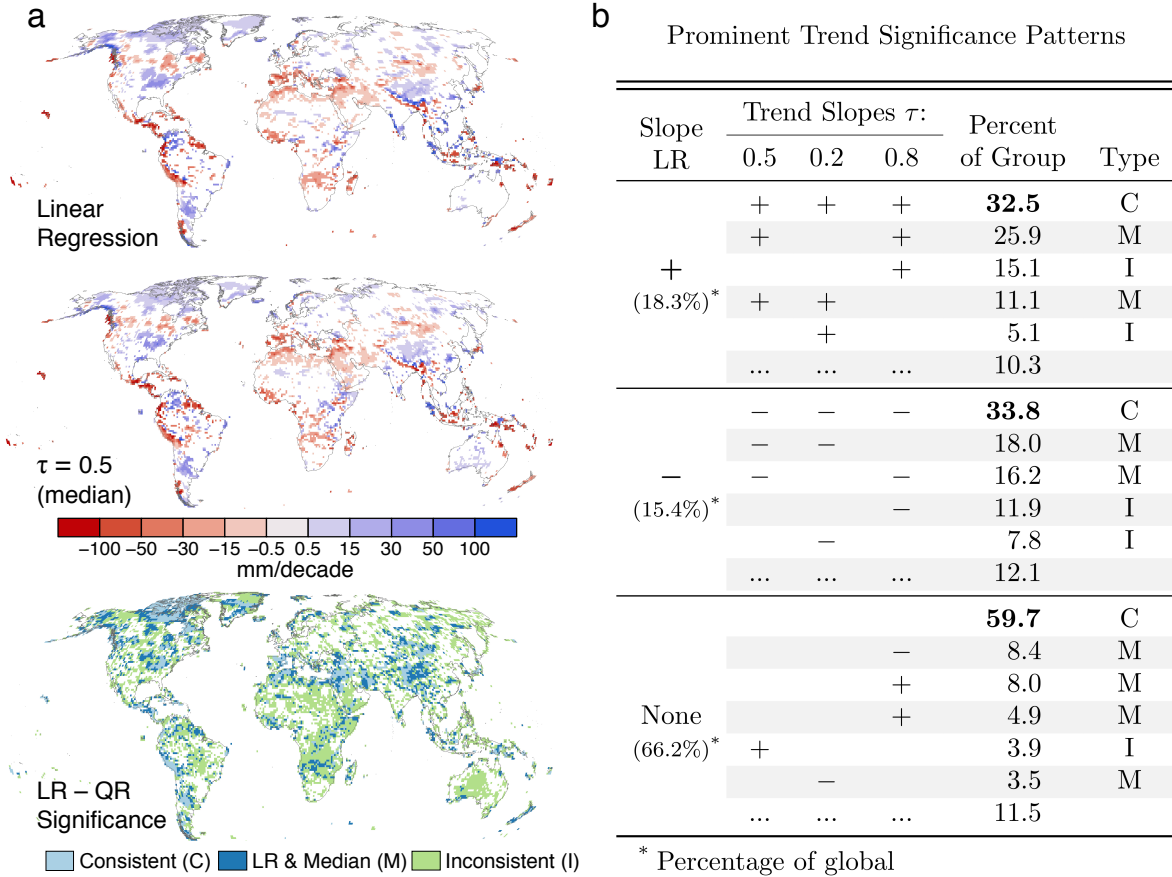


Figure 5.1: Tail trends show inconsistencies with mean and median. a) Spatial distribution of trends estimated by linear regression (LR) and quantile regression (QR) at $\tau = 0.5$ (median). LR-QR significance identifies locations where $\tau = 0.2, 0.5, 0.8$ are all consistent in significance and direction with LR (C), where $\tau = 0.5$ is consistent with LR (M), and where the responses are inconsistent with LR (I). b) Patterns of QR trends grouped by LR, with consistent responses shown in bold. + and - indicate positive and negative trends respectively and are significant at $\alpha = 0.05$.

quantiles in the eastern United States, western South America, northern latitudes of North America, and dispersed throughout areas of Asia comprising 11.2% of all grid cells. An additional 13.4% of grids show consistencies between LR and the median only. However, results show asymmetric trends in all regions with 35.9% of total grids showing inconsistencies between LR and quantiles in significance, direction, or both. Comparing the primary patterns of QR and LR trends at each location highlights the diversity of QR assessed trends, including the 3 possible patterns assumed by a location-shift model

(Figure 5.1b , Table F.1). The tails consistently exhibit asymmetric changes and are most frequently overlooked by conventional methods. The methodology presented here disentangles the trends across quantiles, enabling the identification of changes across specific thresholds (Appendix F , Figure F.4).

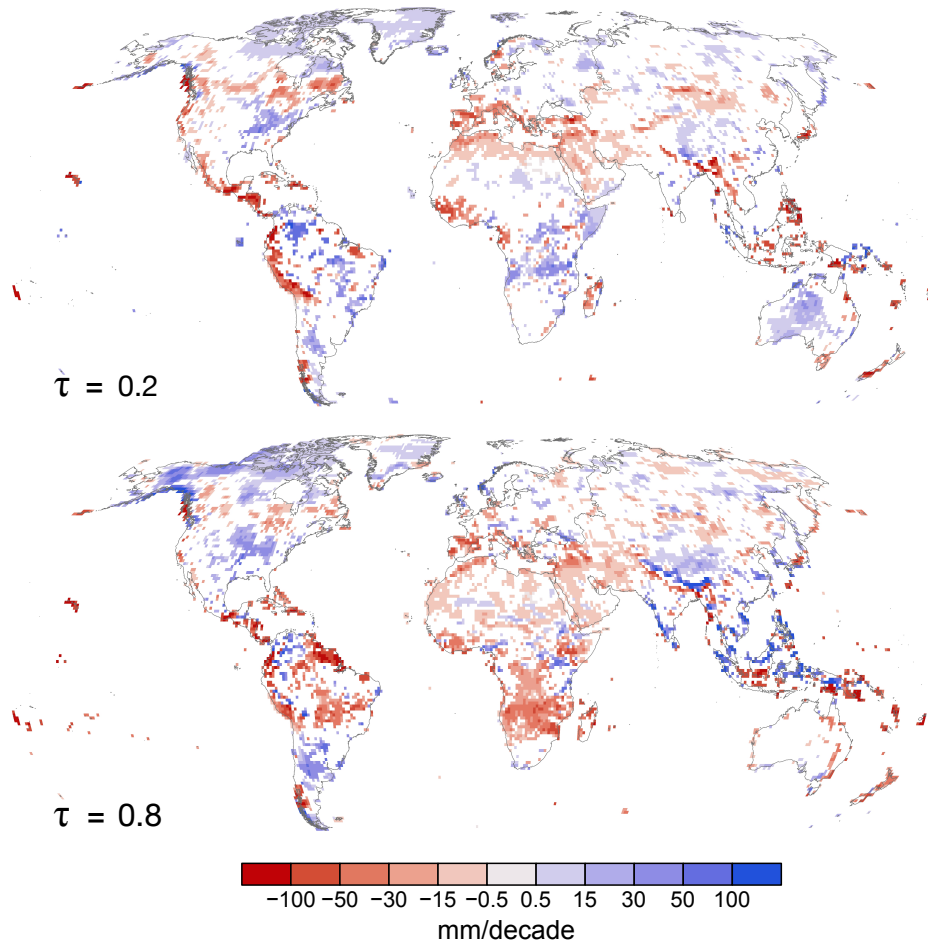


Figure 5.2: Trends in tails show asymmetries in sign, magnitude, and spatial distribution. Trends in $\tau = 0.2$ and $\tau = 0.8$ estimated by QR, and are significant at $\alpha = 0.05$

5.6 Typology of Precipitation Variability and Risk

Large deviations from mean annual precipitation can impart significant stress to human and ecological systems. Thus, simultaneous analysis of trends in the upper and lower tails of the precipitation PDF allows for assessment of the compounded influence of risk and

variability (see Methods). Pairwise combinations of changes in the wet and dry tails, summarized as positive, negative, and no trend, yield 9 distinct patterns that characterize risk and variability (Figure 5.3). The first three elements in the legend indicate consonant tail trends while the remaining 6 indicate sensitivity in either a single quantile or both quantiles with opposing directional responses implying changes in inter-annual variability as well as risk. All regions exhibit cases of single-tail or diverging tail trends, with 38.4% of the global population and 44.4% of land area coinciding with overlooked trends. The most frequently overlooked trends include an increased risk of an extreme wet conditions (high annual total) and increased variability (positive trend in $\tau = 0.8$ only) found in the Midwestern United States, Northern Canada, South-Central Asia, and Indonesia impacting 860 million people globally. Conversely, 840 million people are exposed to a decreased risk

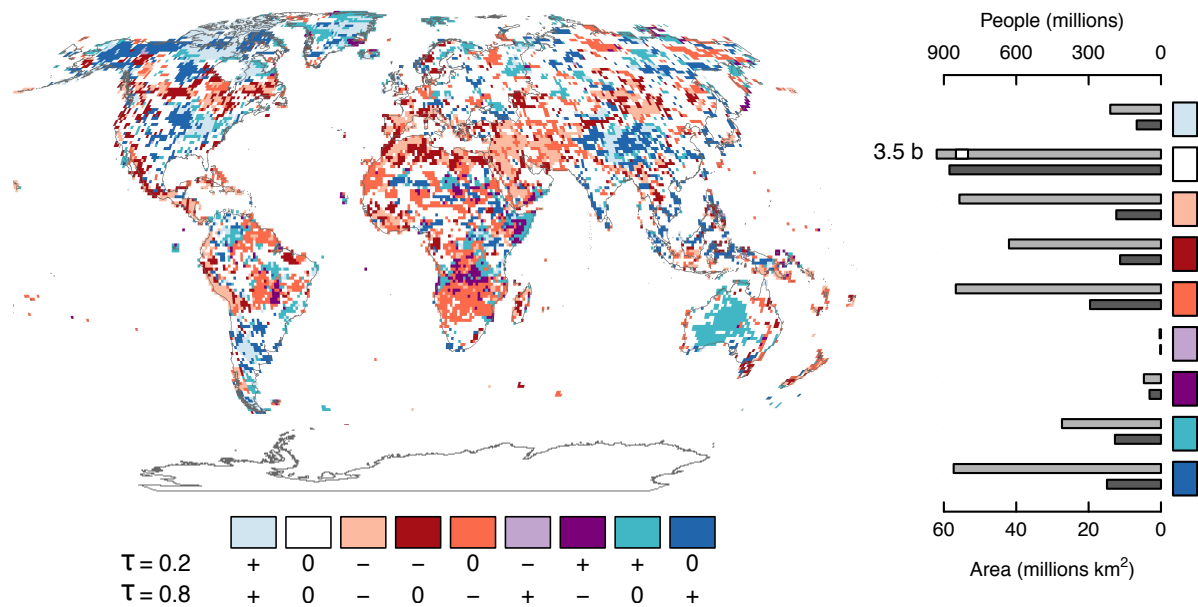


Figure 5.3: Tail typology combines dry and wet tail trends to synthesize variability and risk of precipitation excesses and deficits. All pairwise combinations of positive (+), negative (-), and non-significant (0) trends in $\tau = 0.2$ (dry) and $\tau = 0.8$ (wet) tails. Total land area (black) and population (gray) associated with each type are provided as a bar graph. Greenland is excluded from statistics due to sparse population.

of wet conditions due to negative trends in $\tau = 0.8$, particularly over Southern Africa, South America, and parts of Northern Asia, indicating a decrease in the incidence of high annual totals. An increased risk of dry conditions coincides with 630 million people (negative trends in $\tau = 0.2$) in parts of southern Europe, the western United States, southern Canada, and northern Africa. Such single-tailed trends are not discernible in LR analysis, where a common trend is ascribed to all quantiles. Furthermore, changes in interannual variability are systematically parsed into 3 typologies each whereby for trend significance and direction ($\tau_{0.2}, \tau_{0.8}$): a) increased interannual variability: (0, +), (-, 0), (-, +) and b) decreased variability: (+, 0), (0, -), (+, -). Relatively few areas (2.4%) exhibit significant trends of opposite sign in the upper and lower quantiles, compared to the other 4 types (41.9%). As diversity of changes may entail single or two-tailed trends, QR allows for risk and interannual variability to be assessed in a detailed manner.

A related concern is with trends towards increasing and decreasing annual precipitation in the wettest and driest regions. Grids were ranked by long-term mean annual totals, and land areas corresponding to the 20% highest and 20% lowest totals were used for further analysis. The frequency of typology occurrence shows that 26.7% of the driest land area coincides with negative trends in single or both tails of the PDF, including parts of Northern Africa, the Middle East, and Central Asia. Similarly, 24.2 of the wettest area coincides with positive trends constituting a higher probability of wetter conditions, particularly over the sub-tropics including parts of South America, central Africa, and Indonesia. LR identifies fewer areas than QR, overlooking trends in the wettest and driest regions of the world (Figure F.3), further demonstrating the need for trend reappraisal. In total, 2.8 billion people and 58.8 million km² coincide with changes overlooked by LR-based methods. Trend typologies enable a detailed characterization of the nature of precipitation changes. However, it is noted that the level to which a trend constitutes a significant impact depends on the magnitude of the trend, context, and level of sensitivity, as a system may be more or less sensitive to changes in one tail than the other. The spatial

extent and populations associated with these overlooked trends underscores their importance for understanding potential risk to populations, future water supply, and water-sensitive systems.

5.7 Overlooked Trends in Rainfed Agricultural Systems

To illustrate the implications of overlooked trends on human systems, trends are assessed in areas dominated by rainfed agriculture (Figure 5.4a). Rainfed agriculture is particularly widespread in Africa, Southeast Asia, the Midwestern United States, and Europe, constituting approximately 75% of total agricultural land (Table F.2). It is noted that there are uncertainties in determining the precise location and extent of rainfed and irrigated agriculture (Meier et al., 2018). Rainfed agriculture is more sensitive to changes in precipitation than irrigated agriculture, particularly in locations with low levels of infrastructure and water supply (Elliott et al., 2014). In regions such as Sub-Saharan Africa where there is a high reliance on rainfed agriculture to meet nutrition and economic needs, there may be higher vulnerabilities to changes in climate, demographics, and global trade (van Ittersum et al., 2016). By intersecting trend typologies with land areas characterized by predominantly rainfed land uses, it is shown that 53.7% of all rainfed land area coincides with significant tail trends, with 40.7% characterized by non-consonant tail trends overlooked by LR (Figure 5.4b). Crop-specific precipitation thresholds are sensitive to various aspects of precipitation (annual, seasonal, intensity, frequency), may be sensitive to other climatic variables, and are used to inform management practices. For example, sorghum yields in West Africa increase with precipitation intensity and decrease with more frequent lower level precipitation in years with lower annual rainfall, while at higher annual amounts yields may decrease due to increased nitrogen soil leaching. Regionally, our results show that 57.8% of rainfed area in Africa is characterized by overlooked trends, with more than half showing an increased risk of drier conditions (negative trend in $\tau = 0.2$ or $\tau = 0.8$; Figure 5.4c), primarily over western and southern Africa (Figure 5.3).

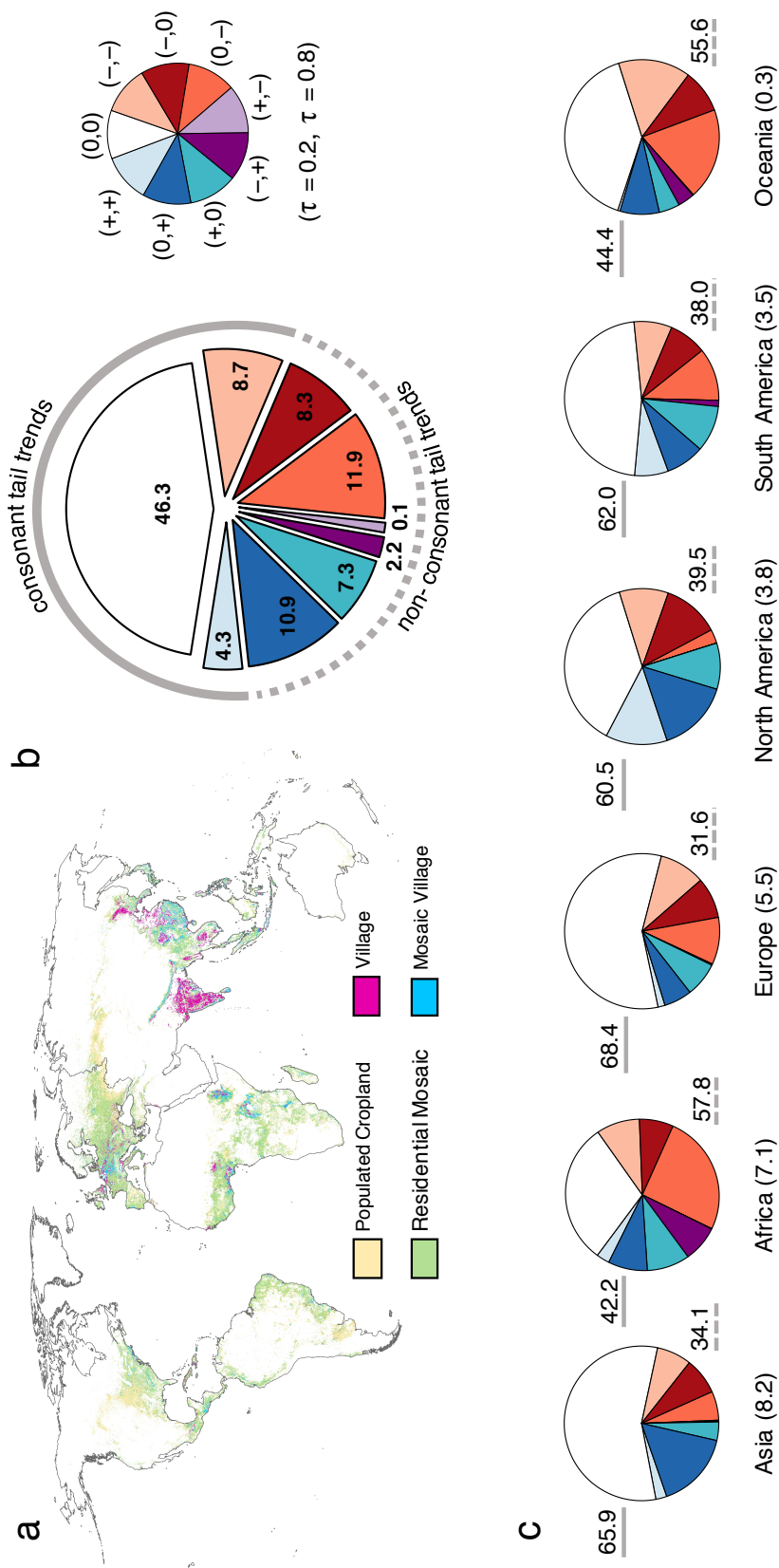


Figure 5.4: Overlooked trends coincide with regions dominated by rainfed agriculture. a) spatial distribution of rainfed land types. b) percentage of rainfed land area coinciding with tail-trend typology. c) percentage of rainfed land in each region associated with tail trends. Total rainfed area in million km² is shown in parentheses. Percentage of land exposed to consonant and non-consonant tail trends are noted to the upper left and lower right of each plot respectively.

Wheat cropping practices in the United States Pacific Northwest and Midwest are also sensitive to precipitation thresholds, with lower yields associated with summer fallow - winter wheat planting practices when precipitation is high as compared to planting directly after other crops, demonstrating the role of precipitation thresholds in determining planting strategies. Results show an increased risk of wet conditions across rainfed agriculture areas in North America, notably in the Midwest region. There are also high sensitivities to overlooked trends in Australia (55.6%) and Asia (34.1%). Given the wide range of crop sensitivities to climatic variables, this illustrated approach may be generalized for assessment at any crop-specific thresholds.

5.8 Implications of Mischaracterized Trends for Risk to Human and Environmental Systems

Human adaptation to climate change requires understanding the likelihood of experiencing detrimental impacts. Mischaracterization of risks to human and environmental systems may underestimate the urgency of climate adaptation or could lead to inappropriate strategies. The results of this chapter show that significant population and land areas on the global scale correspond with changes in precipitation risk and variability and are mischaracterized by conventional approaches. This analysis identifies regions where trends in the lower and upper tails, of high salience for climate impacts assessment, are inconsistent with those in the mean and median. In rainfed agricultural areas – one context where precipitation variability and change inform decision-making and adaptation strategies – QR-based methodology identifies overlooked trends. Furthermore, unreliable or erroneous estimates of risk is of special concern for more vulnerable contexts and communities. These results underscore how trends overlooked in terms of spatial extent, regionality, and severity have implications for a range of human and environmental systems. This is particularly notable given the use of LR-based methods to assess observed and future trends in precipitation; IPCC reports are one prominent example (Trenberth et al.,

2007). Here a reappraisal of risk across thresholds in human and environmental systems is offered, with previously undetected changes present in all regions of the globe. Future work is needed to determine if overlooked trends are replicated in general circulation models – a widely used tool for projecting climate-induced risks to earth systems – and assess how they may change in response to future climate variability. Detection of future trends across a range of thresholds allows for risk assessment at more appropriate adaptation targets.

CHAPTER 6

CONCLUSION

The social-environmental system is increasingly undergoing anthropogenic and natural changes, with degradation and negative impacts experienced by humans and ecosystems alike. While these changes have prompted a shift towards a broader consideration of human-environmental linkages and the associated governance elements that moderate management efforts, key gaps remain. Critically absent is an explicit acknowledgement of equity – particularly in regards to inclusion of peoples, values, and knowledges. Underestimation of risk may further exacerbate existing inequities, underscoring the need for adaptive and equitable water governance. This work has sought to address these issues in three ways:

1. The development of a new conceptual framework to support equitable and adaptive solutions under changing conditions. While aspirational goals in prominent water management approaches point towards the desire for equitable outcomes, equity is not adequately addressed in practice. The Water Resources Stewardship framework presented in this dissertation fills this gap by decomposing the social-environmental system into six interlinked elements with ties to equity: interlinkages across scales, diverse knowledges, inclusion of peoples, values, and place, governance and institution, co-produced solutions, and adaptive risk management. Many of these elements are often subsumed under the umbrella of governance and may be overlooked or under-acknowledged in other approaches. By bridging disciplines, Water Resources Stewardship offers a more comprehensive view of equity than current prominent approaches. Analysis of Integrated Water Management case studies indicate that while the approach has prompted a shift towards consideration of interlinkages between water and other sectors, participation, and multi-level

governance arrangements, it tends to under-acknowledge traditionally underrepresented groups, knowledge, and values. Lack of monitoring and adequate long-term commitment further undermine the more aspirational objectives of IWRM. These findings are consistent with previous studies which indicate that IWRM, while aspirational, lacks tractability (Biswas, 2004, 2008; Medema et al., 2008).

Exploratory analysis of water-based and governance indices suggest that countries with stronger governance regimes may be more equipped to anticipate and adapt to change. Notably, high disparities in virtual water flux are disproportionately present in countries with weaker governance scores. Future work is required to validate the Water Resources Stewardship framework. Application to place-based case studies with different governance contexts, and the development of metrics to track elements of the frameworks are productive lines of inquiry.

2. The delineation of a place-based environmental rulemaking process to identify opportunities and constraints for adaptive policy development. The structure of governance and institutions inherently impacts elements such as inclusivity, knowledge uptake, and how interlinkages among systems are considered. Environmental flow rules seek to broaden issues of water allocation beyond consumptive use concerns. Environmental flows are comprised of flow magnitude, timing, frequency, duration, and rate of change, and have strong interlinkages with ecological health and functioning (Poff et al., 1997). By setting thresholds on water extraction, environmental flow rules seek to balance ecological water needs with human consumption. A delineation of Maine's *Chapter 587: In-stream Flows and Lake and Pond Water Levels* highlights the challenges of resolving diverse needs among water users, addressing critical knowledge gaps, and working within the institutional constraints of a rulemaking process. A 1999-2002 drought event acted as a 'focusing-event' (Birkland, 1998), cutting across sectors, revealing key shortcomings of water governance in Maine, and prompting policy action. An analysis of the

rulemaking structure identified the interdependencies between processes and how one process can constrain or advance another. One key example is how the actions of the state Legislature induced pauses and imposed conditions for rule design, agency coordination, and revision of rules, which directly led to activities such as stakeholder workshops and agency review. This work identifies a lack of attention towards monitoring and changing baselines within the post-rulemaking process, resulting in a current knowledge deficit. In order to achieve the goals of in-stream flow rules, a more active integration of knowledge is needed. New institutional arrangements such as a proposed Water Management Planning Committee present opportunities for introducing mechanisms for learning, policy reappraisal, and triggering policy action. Furthermore, efforts to build stakeholder capacity should include access to knowledge, data, and analyses in order to facilitate learning and a broader understanding of system interlinkages.

Several questions were raised by this work and deserve future consideration. Inclusion of stakeholders is necessary to facilitate broader representation of needs, values, and objectives. However, it is generally impractical to open stakeholder processes to an unlimited number of people (Antunes et al., 2009). Groups or representatives are assumed to represent the underlying population. Future work needs to be done to assess the priorities and values of stakeholder groups to the underlying population and identify underrepresented values. Similarly, adaptive policymaking requires long-term commitments from stakeholders for participation and learning. More work needs to be done to understand what factors may increase likelihood of participation in rulemaking procedures. Finally, the case study contributes to understanding the structure of the rulemaking process at the state-level – an understudied area (Crow et al., 2017). Application of this approach to other state-level environmental flow rules and case cross-comparisons are necessary for identification of commonalities or unique features.

3. Advancement of statistical methodology for assessing precipitation and risk to social-environmental systems. A critical shortcoming of conventional risk approaches is that statistical methods used to assess trends make restrictive assumptions regarding variance and central tendency. Chapters 4 and 5 make methodological advancements in this area by developing a quantile regression risk approach. Key results include a) the annual precipitation is sensitive to the leading statistical patterns of sea-surface temperature (SST), and b) precipitation response to SST is asymmetric across quantiles, covariates, and varies regionally. Therefore, both the phase and magnitude of SST indices moderate the response in the precipitation PDF. In Chapter 5, it is shown that 44.4% of total global land area and 40.7% of the population are exposed to trends in the $\tau = 0.2$ and $\tau = 0.8$ quantiles (representing high and low precipitation totals) that are inconsistent with the mean trend. LR mischaracterizes or overlooks trends in terms of spatial extent, regionality, and severity leading to systematic over or underestimation of risk. A typology of quantile response highlights the diversity in combinations of risk and variability detected by QR approaches. An extension to rainfed agriculture illustrates how overlooked trends may have implications for water-dependent sectors. Critically, undetected or erroneous calculation of risk could lead to inappropriate adaptation strategies. The risk-based climate estimate approach presented here offers a solution to the shortcomings of conventional approaches and shows alignment with stewardship elements. The ability to detect changes at user-specified thresholds provides opportunities for inclusion of stakeholders and production of co-produced solutions. Identification of thresholds and decision-needs can benefit from the inclusion of experiential knowledge. Furthermore, harnessing climate-based information to develop conditional risk estimates can be used to support tailored decision-making and aid in identifying appropriate adaptation strategies.

This work offers opportunities for new lines of inquiry including: a) determination if overlooked trends are replicated in general circulation models and how they may respond to future climate variability, b) assessment of risk for different systems (e.g. agriculture, water supply systems) at appropriate scales and targets to inform adaptation strategies, c) modeling studies to understand how asymmetries in precipitation may manifest in hydrologic systems and what these relationships may imply for risk, and d) identification of opportunities for integration of the method within decision-making processes to identify appropriate thresholds for analysis.

Taken together, this work has provided contributions to the areas of water resources management and hydrology. The Water Resources Framework decomposes the social-environmental system into key elements that require more focused attention. The approach places special attention on governance and how governance structure and the ways in which policies are made may enable or constrain the other framework elements. Chapter 3 addresses this dynamic through analysis of a state-level rulemaking structure. While limited in scope to a single policy, it provides insights into the ways in which integration of knowledge, values, and needs may be constrained or enabled. Identification of opportunities for integrating adaptive elements into policymaking seeks to redress existing shortcomings. Finally, chapters 4 and 5 provide a methodological advancement for assessing change at any user-specified threshold to a) enable risk assessment at more appropriate adaptation targets, and b) inform future decision-making.

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APPENDIX A

SUPPLEMENTAL MATERIAL FOR CHAPTER 2

A.1 Disciplinary Approaches to Human and Environmental Relationships

Parallel to the development of these declarations, knowledge and approaches seeking to understand human relationships with the environment, including water, have been organized in various disciplinary arenas. These framings offer an important point of reference for the basis of current and future approaches as well as informing policy developments. We highlight some lines of inquiry including:

- a. **Ecology:** Understanding impacts to ecosystem health and functioning and approaches to pursue environmental conservation. This includes adaptive management (e.g. Holling and Meffe, 1996; Holling, 1978) to anticipate and learn from change and increase system resilience, environmental flow approaches for linking riverine flow to ecosystem health (Poff et al., 1997; Arthington, 2012), and more recently approaches for navigating social-ecological change (Chapin et al., 2011).
- b. **Policy Sciences and Economics:** focus on aspects of governance of social-environmental systems (SES). This includes scholarship on indigenous knowledge and community-based governance (Berkes, 2004; Ostrom, 2009; Marín and Berkes, 2010), the benefits people derive from ecosystems (Constanza et al., 1999), economic considerations of ecosystems for more equitable trade-offs (Tallis and Polasky, 2009; Dasgupta, 2014), and adaptive governance approaches (Dietz et al., 2003; Folke et al., 2005).
- c. **Anthropology:** understanding human relationships with the environment including contemporary (e.g. Nadasdy, 2003; Roncoli, 2006) and historical perspectives (e.g. Dillehay et al., 2004) of how communities observe and respond to change. This

includes understanding the manner in which natural and human forces shape societal well-being and conditions (Crate and Nuttall, 2009; Vásquez-León, 2009).

- d. **Engineering and Hydrology:** traditionally focused on understanding the variability and increasing the predictability of natural systems. A related arena involves the use of structural and non-structural measures to manage water resources. Emerging approaches include socio-hydrology for understanding feedbacks in human-environmental systems from a hydrologic perspective (e.g. Sivapalan et al., 2014), and Water Security (Vörösmarty et al., 2010; Srinivasan et al., 2017) which uses technical approaches to ensure the sustainable provision of water to ensure human livelihoods and health.

Disciplinary arenas such as Earth Sciences and related sub-disciplines (e.g. National Research Council, 1991, pg. xi), Geography (e.g. National Research Council, 1997), and Sociology (Dunlap and Catton, 1979; Zehr, 2014) are also recognized as important contributors among other disciplines not expanded upon here. Collectively, these disciplines reflect a diverse understanding of human-environment interactions, with overlapping motivations and components.

A.2 Keyword Count Methodology

Case studies were selected according to the following criteria: a) is included in a peer-review book or journal, b) multiple elements of IWRM must be considered, c) cases must refer to a specific implementation of an IWRM policy, opportunities for potential IWRM implementation were not considered d) has a definition matching or similar to the cited GWP definition. For the purposes of regional comparisons, the EU Water Framework Directive was considered a regionally-tailored version of IWRM as were specific initiatives in the US, Canada, and Australia. To add context to findings, additional studies not meeting these criteria were used in the regional synthesis.

A set of key themes were deductively selected from IWRM literature, falling under the key themes of Society, Environment, and Economy comprising a total of 18 keywords. Due to the IWRM guidance document emphasis on monitoring instruments, keywords associated with adaptive management were also considered. In IWRM literature, the word ‘sustainability’ is often invoked without context, while other times it is used in terms of ‘economic sustainability’ or ‘ecological / environmental sustainability’. A general use of the term was included in instances where it was not defined by context. Each case study was coded according to the set of keywords. Titles, abstracts, keywords, figures, tables, captions, and references were omitted. Non-case study background describing IWRM as a concept was also disregarded. Synonyms of keywords were also included where appropriate. For example, environmental and ecological were considered interchangeable in the context of environmental health and well-being. We note that mention of a keyword does not indicate success or failure of implementation, and no distinction is made between positive and negative uses of terms.

A.3 Statistical Leading Patterns of Governance Indicators

The Worldwide Governance Indicators [WGI; (Kaufmann et al., 2010)] for the most recent available year of data (2016) was used to characterize governance (Figure A.2). The most recent available year of data was used. We note that tracking changes in governance over time is inappropriate with this dataset. Similar values for all indicators are shown on the global scale, with higher scores in the US and Canada, Oceania, and Europe, and lower scores in parts of Africa, the Middle East, and Asia. However, variation among indicators is evident. For example, parts of Asia show higher scores for government effectiveness, but lower scores for other indicators. Principal Component Analysis (PCA) was used to identify which indicators tend to vary together, and if specific indicators account for a high level of variance. PCA reduces information from multiple variables into fewer variables through linear combinations of data, producing leading patterns of variability that are

uncorrelated (Jolliffe, 2002). The WGI indicators are already normalized and did not require any pre-processing prior to PCA.

The first principal component (PC1) is the linear combination of variables with the highest variance. The second pattern (PC2) explains 7.5% of the variance, with subsequent patterns explaining low levels of variance (Figure A.3). PC2 is negatively correlated with Voice and Accountability (VA) and Political Stability (PS) while the remaining indicators show low positive correlation. As such, high PC2 scores indicate that VA and/or PS diverge from the other indicators. For example, While the US, Canada, Australia, and much of Europe show higher PC1 scores indicating stronger governance compared to other locations, they show strong to moderate PC2 scores (Figure A.4). This is due to lower political stability scores in those locations compared to the other indicators. Conversely, many countries in the Middle East and parts of Asia have high PC2 scores due to low VA. Countries with low scores (-0.25 to 0.25) are characterized by similar scores across all indicators. For countries with weak PC1 scores (-0.5 to 0.5) and stronger PC2 scores, governance is characterized primarily by a few of the indicators.

As a few countries tend to dominate the global PC patterns on the global scale —both positively and negatively, PCA was also conducted on the regional scale. Countries were subset into geographically similar regions and PCA was performed on each region independently. WGI were rescaled and centered during the process to account for variation in each region. As with the global PCs, PC1 dominates the regional variability with similar positive correlation across all indicators (Figure A.5). The Middle East / North Africa region is the exception, where VA is less correlated than the others. Unlike with the global PC1, within each region the countries with stronger and weaker governance can be identified. For example, parts of Southern and Western Africa show strong governance compared to the rest of the region where in the global PC1, little variation is found. PC2 shows varying correlation across indicators by region. This adds context to the global PC2 by highlighting which indicators are responsible for strong positive and negative scores in

the global PC2. For example, the regional PC2 confirms that positive scores indicate higher PS and low VA in MENA while in North America the opposite is true.

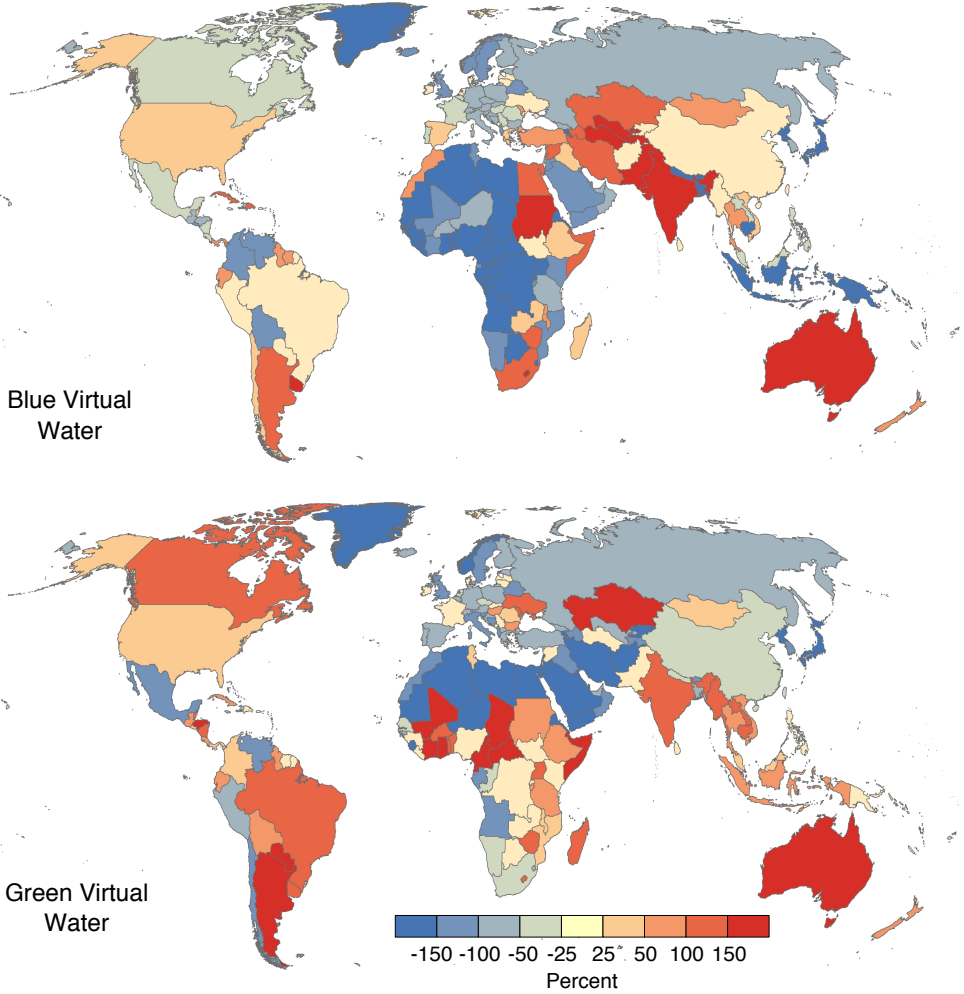


Figure A.1: Percent difference between Blue and Green virtual water exports and imports. Total volumes are average flux during the period 1996-2005. Percentages are expressed as $\frac{Export-Import}{AverageFlux} * 100$

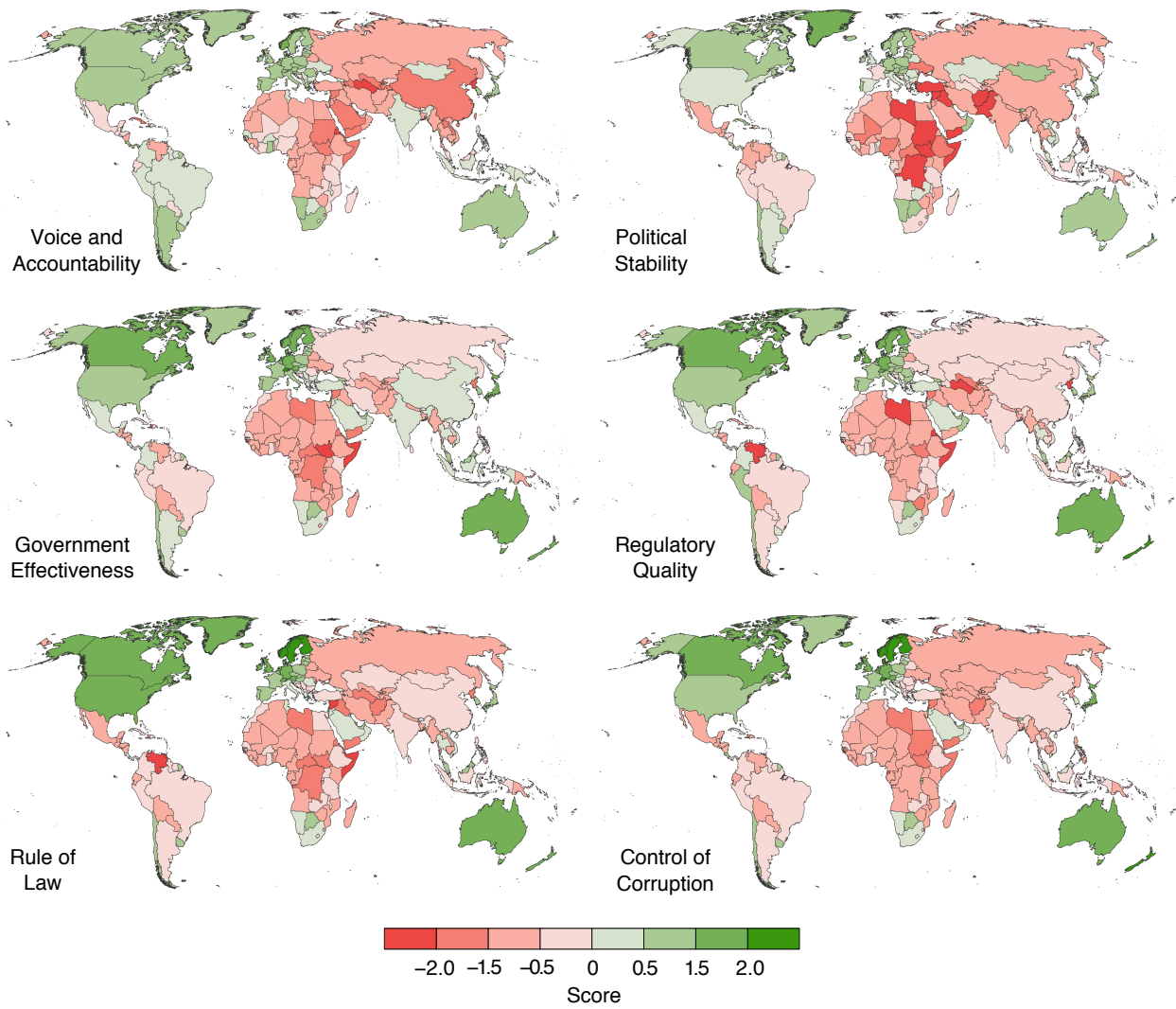


Figure A.2: Worldwide Governance Indicators 2016

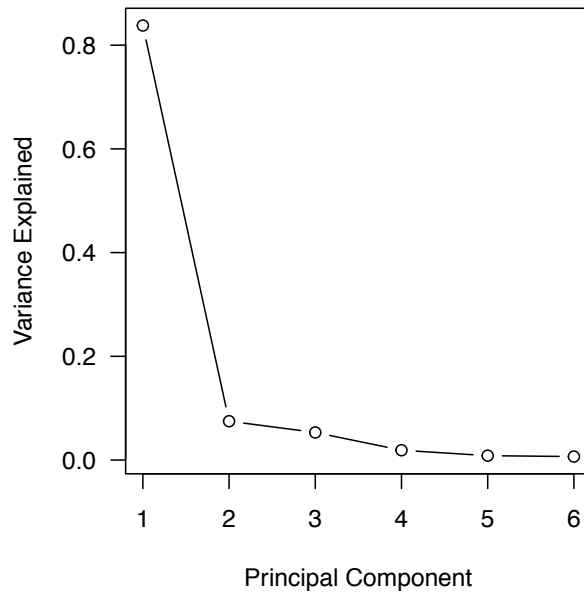


Figure A.3: Global WGI PCA variance explained.

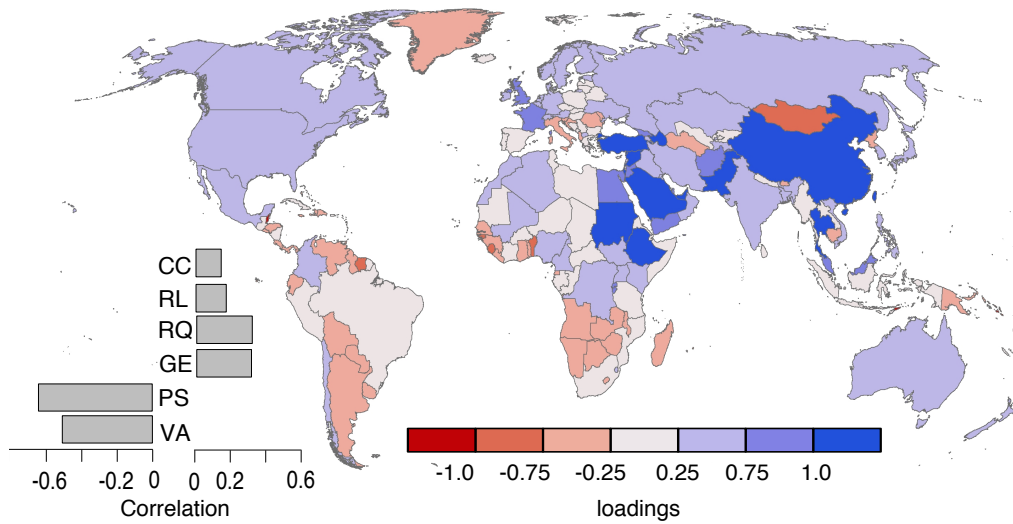


Figure A.4: Second leading statistical pattern of WGI and correlation with corresponding indicators.

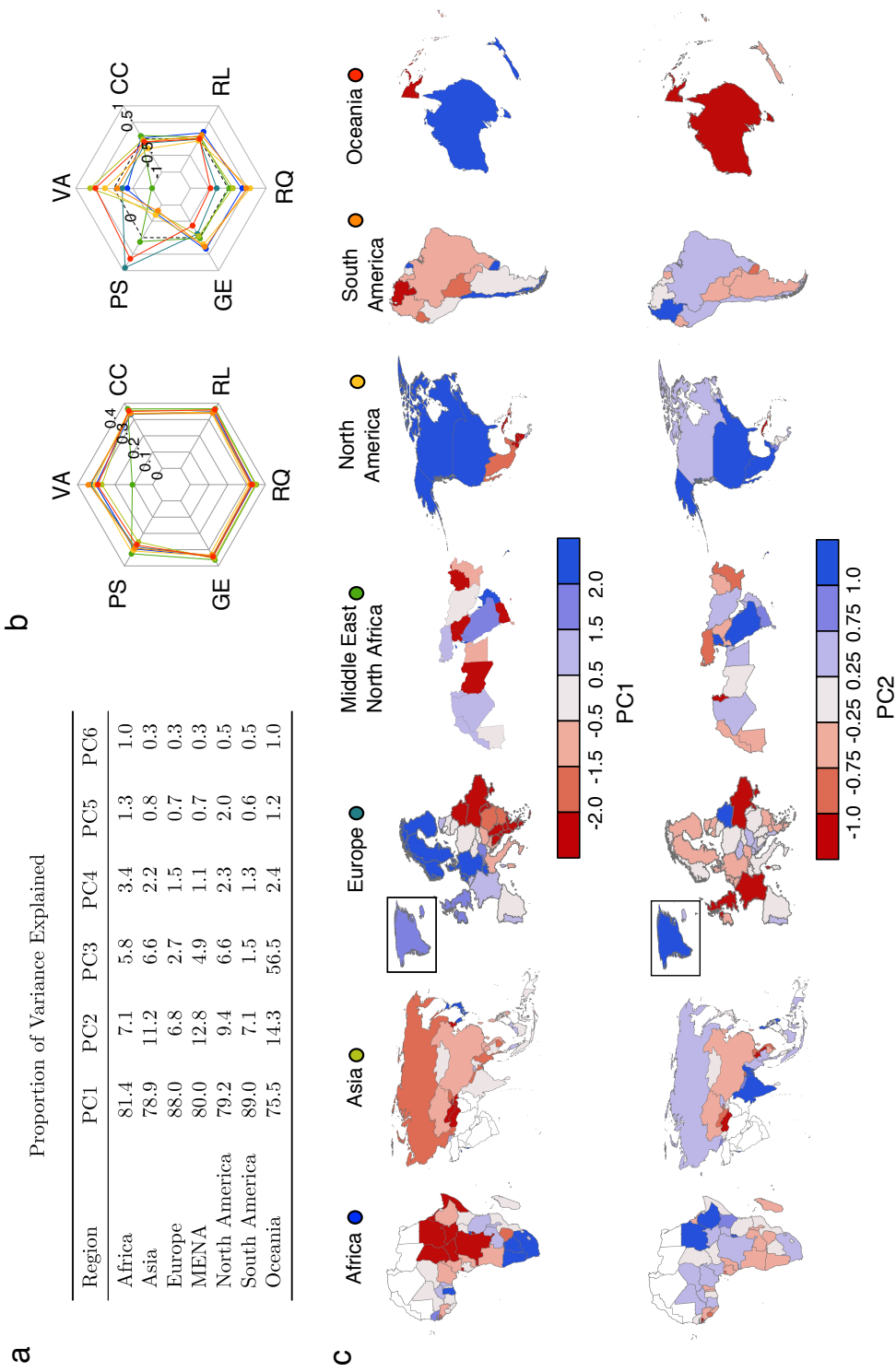


Figure A.5: Regional statistical leading patterns of worldwide governance indicators. a) Variance explained (%) by each pattern (PC) within each region. b) Correlation of the first and second leading patterns with each indicator by region. Colors are denoted below. c) Regional PC1 (top) and PC2 (bottom).

APPENDIX B
MAINE CHAPTER 587: IN-STREAM FLOWS AND LAKE AND POND
WATER LEVELS

Chapter 587: In-stream Flows and Lake and Pond Water Levels

SUMMARY: This Chapter establishes river and stream flows and lake and pond water levels to protect natural aquatic life and other designated uses in Maine's waters. Instream flow requirements for Class AA, A, B, and C waters are based on natural flows that occur in Maine waters, and the uses and characteristics assigned by the water quality classification program (38 M.R.S.A. Sections 464, 465) with attention given to protecting the outstanding natural resources associated with Class AA waters. Flow is managed to provide natural variation of flow described by seasonal aquatic base flows, or other seasonally variable flows, shown to protect aquatic life resources and water quality standards. Water level requirements for Class GPA waters take into account natural variation of water levels that occur in Maine lakes and ponds, and the uses and characteristics assigned by the water quality classification program (38 M.R.S.A. Sections 464, 465-A). Water level is managed to provide variation that takes into account expected seasonal levels shown to protect aquatic resources and other water quality standards of Class GPA and downstream waters. Instream flows and water levels may be established by 3 methods: (1) standard allowable alteration, (2) by a site-specific flow designation developed through an Alternative Water Flow or Alternative Water Level, or (3) as part of a new or existing regulatory permit. A water use which fails to comply with the requirements of these rules is subject to penalties pursuant to Title 38, Section 349.

1. **Applicability.** The requirements established herein apply to withdrawals or other direct or indirect removal, diversion, activities, or use of these waters that causes the natural flow or water level to be altered for all non-tidal fresh surface waters of the State. Notwithstanding this, the flows and water levels established in this chapter do not apply to the following circumstances.

A. **Public Emergency.** Alteration of flow or water level for the purpose of protecting public health, safety, and welfare due to a sudden catastrophic event, such as for fire control. This includes water withdrawals for emergency preparedness.

B. **Storage ponds.** Ponds constructed outside of a natural stream channel for the purpose of storing water for later use, such as irrigation or snowmaking, or other man-made ponds not classified GPA under 38 M.R.S.A. Section 465-A.

C. **Nonconsumptive use.** Nonconsumptive use of water is defined in 38 M.R.S.A. Section 470-A. Notwithstanding this, an existing (as of the effective date of this chapter) point of return flow to contiguous water greater than 1/4 mile from the point of withdrawal and that otherwise meets the definition of nonconsumptive use in 38 M.R.S.A. Section 470-A, is also deemed to be a nonconsumptive use. For the purposes of this chapter, non-consumptive use is determined to have no measurable effect on flows or water levels. Flows in the segment between a point of withdrawal and a downstream point of return must be sufficient to maintain all other water quality standards, including all designated uses and characteristics of the assigned classification. Activities that constitute a nonconsumptive use may occur during all flow and water level conditions.

D. **Existing Community Water Systems operating with a Community Water System Withdrawal Certificate.** Except as provided herein, Community Water Systems must comply with the applicable flow and water

level requirements established in sections 4, 5, 6, 7 or 8 of this chapter. Notwithstanding this, and for the purpose of any enforcement action under this chapter, these requirements will not apply to an existing Community Water System operating within its system design capacity providing that (1) the Community Water System, so operating, cannot attain the applicable requirements, and (2) the Community Water System has received, and is operating in accordance with, or is otherwise satisfying the requirements of, a Community Water System Withdrawal Certificate issued by the Department. A Community Water System Withdrawal Certificate will be issued by the Department to any existing Community Water System that demonstrates that it cannot operate at its system design capacity and attain the applicable flow or water level requirements of this chapter. Existing Community Water Systems are those systems that are operating and withdrawing water for customer use as of the effective date of this rule. A certificate shall allow withdrawals for Community Water Systems up to their system design capacity. A certificate may include appropriate conditions that take into account the economic and technical feasibility of maintaining, and restoring to the extent feasible, all water quality standards affected by the Community Water System, including all designated uses and characteristics of the assigned classification. Economic and technical feasibility shall consider the provisions of their Legislative charter or other authority, watershed protection benefits of the existing source, and the financial viability of the Community Water System provided that the conditions and limitations of the certificate can be accomplished within the existing Public Utilities Commission approved rate schedule(s) of the system or do not in and of themselves cause a Community Water System to request a rate increase to their customers. In implementing the conditions of a certificate, the Community Water System may choose to incorporate the cost of compliance into their

long-range capital plan. Any conditions included in a Community Water System Withdrawal Certificate must be reviewed and approved by the Drinking Water Program at the Department of Health and Human Services with technical assistance from the Office of the Public Advocate on economic issues, before being issued by the Department of Environmental Protection, to assure they are economically affordable and technically feasible, and will not jeopardize the safety, dependability, or the financial viability of the Community Water System. All water quality standards, as well as flows and water levels established pursuant to this chapter, remain applicable to the waters affected by the Community Water System, and will be used to assess water quality in those waters for all other purposes. The intent of the certificate process shall be to accommodate needs of Community Water Systems while striving to move towards achievement of water quality standards.

The Department may issue an amended Community Water System Withdrawal Certificate for an existing Community Water System planning a new or modified source that increases its system design capacity. Any amended certificate shall contain conditions ensuring that all water quality standards affected by the Community Water System, including designated uses and characteristics of the assigned classification, shall be maintained, or improved to the extent economically affordable and technically feasible if they were not previously in attainment. Any conditions included in an amended Community Water System Withdrawal Certificate must be reviewed and approved by the Drinking Water Program at the Department of Health and Human Services with technical assistance from the Office of the Public Advocate on economic issues, before being issued by the Department of Environmental Protection to assure they are economically affordable and technically feasible, and will not jeopardize the safety, dependability, or the financial viability of the Community Water System.

2. Definitions

- A. **Natural drought condition.** “Natural drought condition” means moisture conditions as measured by the Palmer Drought Severity Index with values of negative 2.0 or less.
- B. **Natural variation of flow.** “Natural variation of flow” in rivers and streams is the expected dynamic fluctuation in flow that naturally occurs daily, seasonally and inter-annually that provides for physical characteristics of depth, volume, and velocity necessary to (1) provide habitat conditions for all life stages of indigenous aquatic organisms, (2) provide water exchange and aeration including the interstitial water, substrate scouring and sorting, temperature moderation, wetland replenishment, sediment erosion and deposition, and channel formation, and (3) maintain biological processes of ingress and egress to habitats, migration, drift, insect emergence, organic matter and nutrient cycling, and wetlands maintenance. In establishing site-specific water flows as set forth in sections 7 and 8 of this chapter, flow variation of a magnitude, rate of change, seasonal timing, and annual occurrence, including provision for infrequent passage or release of flood flows, must be sufficient to adequately provide for the conditions and processes identified above.
- C. **Natural variation of water level.** “Natural variation of water level” in lakes and ponds is the expected dynamic fluctuation in water level that occurs seasonally and inter-annually that provides for physical characteristics of depth and volume necessary to (1) provide habitat conditions for all life stages of indigenous aquatic organisms, (2) provide water levels sufficient to support important physical processes including thermal stratification, temperature moderation, wetland replenishment, sediment erosion and deposition, (3) maintain biological processes of ingress and egress to habitats, maintenance of primary production, migration and movement of organisms, organic matter and

nutrient cycling, and wetlands maintenance. In establishing site-specific water levels as set forth in sections 7 and 8 of this chapter, variation of a magnitude, rate of change, seasonal timing, and annual occurrence, including provision for infrequent flood levels, must be sufficient to adequately provide for the conditions and processes identified above.

D. **Normal high water.** “Normal high water” means that elevation determined from a line along the shore of a Class GPA waterbody which is apparent from visible markings, changes in the character of soils due to prolonged action of the water, or from changes in vegetation and which distinguishes between predominantly aquatic and predominantly terrestrial habitat.

E. **Seasonal aquatic base flow.** “Seasonal aquatic base flow” is a median flow value for the following seasons: winter (January 1 to March 15), spring (March 16 to May 15), early summer (May 16 to June 30), summer (July 1 to September 15), fall (September 16 to November 15), and early winter (November 16 to December 31). Seasonal aquatic base flows are established as follows.

- (1) (1) For the winter season January 1 to March 15: a flow equal to the February median monthly flow as determined according to section 3 of this chapter.
- (2) For the spring season March 16 to May 15: a flow equal to the April median monthly flow as determined according to section 3 of this chapter.
- (3) For the early summer season May 16 to June 30: a flow equal to the June median monthly flow as determined according to section 3 of this chapter.
- (4) For the summer season July 1 to September 15: a flow equal to the August median monthly flow as determined according to section 3 of this chapter.

- (5) For the fall season September 16 to November 15: a flow equal to the October median monthly flow as determined according to section 3 of this chapter.
- (6) For the early winter season November 16 to December 31: a flow equal to the December median monthly flow as determined according to section 3 of this chapter.

F. System Design Capacity. “System design capacity” for authorized Community Water Systems withdrawing from surface waters shall be determined by the Department of Health and Human Services as the amount of water that is available for Community Water System purposes expressed as annual withdrawal in total gallons per year taking into consideration actual documented annual withdrawal, and the investments in and limits of the existing system infrastructure, that provides a safe and dependable supply of water for public use. Existing system infrastructure includes water treatment and distribution facilities and other necessary structures that determine how much water can be safely and dependably supplied that is present or in the process of being acquired such as through an investment bond, contractual agreement, or purchase order as of the effective date of this chapter.

G. Water User. For the purposes of this Chapter, “water user” means a person whose withdrawal or other direct or indirect removal, diversion, activity, or use of these waters by means of a structure or facility causes the natural flow or water level to be altered in any non-tidal fresh surface waters of the State.

3. Calculation of seasonal aquatic base flow values

A. Using flow records. Seasonal aquatic base flow is determined using flow records where adequate flow records are available for a specific waterbody. “Adequate flow records” means a minimum of 10 years of U.S. Geological Survey gauging

records, or other equivalent flow records of good quality from unregulated waters, except as follows or as approved by the department.

- (1.) Where the period of flow record is at least 1 year, the available flow records may be extended by means of flow data from a nearby watershed with similar hydrologic characteristics and a minimum of 10 years of U.S. Geological Survey gauging records or other equivalent flow records.
- (2.) Where flow records are unavailable, flow records may be established by using a drainage area adjustment ratio for records from other gauged sites within the same drainage with at least a ten year period of record, and where the drainage areas of the gauged and ungauged sites differ by no more than 50%.

B. Without using flow records. Estimates of seasonal aquatic base flow may be calculated using the most appropriate of the following publications, or by use of a regional flow study to establish seasonal median flows for rivers and streams within a region. An adequate regional flow study should be based on a minimum of 20 stations where at least 10 independent base flow measurements have been made for each site. Where conditions, such as watershed area, fall outside of the conditions by which these estimates were calculated, estimates of seasonal aquatic base flow are considered as interim estimates and may be refined as new site-specific data is obtained.

“Estimating Monthly, Annual, and Low 7-Day, 10-Year Streamflows for Ungaged Rivers in Maine”, USGS Scientific Investigations Report 2004-5026

“August Median Streamflow on Ungaged Streams in Eastern Aroostook County, Maine” USGS Water Resources Investigations Report 2003-4225

“August Median Streamflow on Ungaged Streams in Eastern Coastal Maine”, USGS Scientific Investigations Report 2004-5157

4. **Flow requirements for Class AA waters**

A. **Narrative requirement for Class AA waters.** Except as provided for in this section, flows in Class AA waters shall be maintained as they naturally occur. Withdrawal or other direct or indirect removal, diversion, activity, or use of these waters that causes the natural flow to be altered may occur as provided in paragraph 4-B below.

B. **Flow established by standard allowable alteration for Class AA waters.** Flow in Class AA waters may not be less than the amounts defined in subparagraphs (1), (2) and (3) below, except when natural conditions alone cause those flows to be less, or as provided by an Alternative Water Flow or regulatory permit as established in sections 7 or 8 of this chapter.

- (1) When natural flow exceeds the spring aquatic base flow, 90% of the total natural flow shall be maintained.
- (2) When natural flow during the early winter season exceeds the early winter aquatic base flow, 90% of the total natural flow shall be maintained.
- (3) When natural flow in any other season, except as described in (1) and (2) above exceeds 1.1 times the seasonal aquatic base flow and exceeds 1.5 times seasonal aquatic base flow if aquatic base flow was calculated from methods in paragraph 3-B, 90% of the total natural flow shall be maintained.

5. **Flow requirements for Class A, B, and C waters**

A. **Narrative requirement for Class A, B, and C waters.** Withdrawals or other direct or indirect removal, diversion, activity, or use of Class A, B, or C waters must maintain flows sufficient to protect all water quality standards

including all designated uses and characteristics of the assigned class unless as a naturally occurring condition. When flow alteration occurs in Class A, B, or C waters that drain to a downstream Class AA water, the Class AA flow requirement, provided in section 4 of this chapter, shall be protected.

Withdrawal or other direct or indirect removal, diversion, activity, or use of these waters that causes the natural flow to be altered shall occur as provided in paragraphs 5-B or 5-C below.

B. Flow requirements for Class A waters. Flow requirements established by the standard allowable alteration in Class A waters may not be less than the seasonal aquatic base flow as defined, except when natural conditions alone cause those flows to be less. Withdrawal or other direct or indirect removal, diversion, activity, or use of Class A waters may not occur for more than two consecutive seasons under the standard allowable alteration. The Commissioner may establish, pursuant to sections 7 or 8 of this chapter, site-specific water flows that are protective of all water quality standards, including all designated uses and characteristics of those waters.

C. Flow requirements for Class B and C waters. Flow requirements established by the standard allowable alteration in Class B and C waters may not be less than the seasonal aquatic base flow as defined, except when natural conditions alone cause those flows to be less. The Commissioner may establish, pursuant to sections 7 or 8 of this chapter, site-specific water flows that are protective of all water quality standards, including all designated uses and characteristics of those waters.

6. Water level requirements for Class GPA waters. Except as provided for in this section, water levels of Class GPA waters shall be maintained as they naturally occur. Withdrawal or other direct or indirect removal, diversion, activity or use of these

waters that causes the natural water level to be altered shall occur as provided in paragraph 6-A below.

A. **Water level established by standard allowable alteration.** Water levels in Class GPA waters may not be less than the levels defined in subparagraphs A(1-3) below, except when natural conditions alone cause those levels to be less, or where the Commissioner has determined, as established in sections 7 or 8 of this chapter, that site-specific water levels may be established that are protective of all water quality standards, including all designated uses and characteristics of those waters.

(1) **Class GPA waters without a natural surface water outlet.** Water levels must be maintained within the seasonal levels listed below, unless as a naturally occurring condition:

- (a) within 1.0 foot of the normal high water from April 1 to July 31; and,
- (b) within 2.0 feet of the normal high water from August 1 until March 31.

(2) **Class GPA waters with a natural surface water outlet, including beaver dams.** Water level must be maintained within the seasonal levels listed below, unless as a naturally occurring condition:

- (a) within 1.0 foot of normal high water from April 1 to July 31; and,
- (b) within 2.0 feet of normal high water from August 1 to March 31.

Flow in the outlet stream must be sufficient to maintain seasonal aquatic base flow, as defined in sections 4, 5, 7, or 8 of this chapter with adjustment for evaporation loss from the Class GPA water, or the natural inflow minus evaporation, whichever is less.

3. **Class GPA waters where the water level is controlled by a dam and is not used for hydropower storage or generation.** Water levels

must be maintained to meet all applicable water quality standards, including all designated uses and characteristics of Class GPA waters, and flow must be provided for downstream waters that will protect all water quality standards applicable to those downstream waters. Withdrawal for agriculture, aquaculture, commercial, or industrial purposes will be limited to a volume of water that is no greater than:

- (a) 1.0 acre-foot of water per acre of the waterbody at normal high water from April 1 to July 31. Additional volume increments may be withdrawn whenever it can be demonstrated that water replacement has occurred; and,
- (b) a total of 2.0 acre-feet of water per acre of the waterbody at normal high water from August 1 to March 31. Additional volume increments may be withdrawn whenever it can be demonstrated that water replacement has occurred. In no case may withdrawal cause the water level to be less than the lowest water level that can be achieved through operation of the dam.

Notwithstanding the above limitations on water withdrawal amounts from GPA waters, water withdrawal may not diminish the total volume of the waterbody by more than 25%.

If a dam is removed on a Class GPA waterbody, the standard allowable alteration of water level is that alteration provided in subparagraph 6-A(2) above.

7. Alternative Water Flows and Alternative Water Levels. Alternative flows or water levels may be established following the procedure described in paragraphs 7-A and 7-B below, that allows for withdrawal, diversion, activity, or other use based on

the results of a site-specific flow or water level study that is found by the Commissioner to be protective of all water quality standards, including all designated uses and characteristics, and taking into account the need for natural variation of flow or natural variation of water level by indigenous aquatic organisms and the processes needed to maintain those resources. The Alternative Water Flow or Alternative Water Level will be made available for a 30 day review by other state natural resource agencies and the public before being approved by the Commissioner.

A. A water user or a state natural resource agency requesting an Alternative Water Flow or Alternative Water Level pursuant this paragraph shall use a form provided by the Department and shall include the following information in their filing. The information for the filing shall be developed with the assistance of the Department.

- (1) The location of the proposed withdrawal.
- (2) The amount, duration and frequency of the proposed withdrawal.
- (3) A description of the water use, including assessment of any best management practices or water conservation practices relevant to the type of water use.
- (4) The water flows or water levels that the water user proposes to maintain at the point of withdrawal, including alternative flows or water levels and management provisions that may be implemented when natural drought conditions occur.
- (5) A plan for maintaining the proposed water flows or levels, including a monitoring plan that provides information on water use and flows or levels with a monitoring schedule reasonably sufficient to monitor compliance with the proposed flows or levels.

- B. Upon receipt of a proposal for an Alternative Water Flow or Alternative Water Level, the Department will schedule a field visit to assess the waterbody and the potential impacts of the proposed flows or water levels on aquatic life use and all other water quality standards relating to the waterbody, taking into account the need to protect natural variation of flow or natural variation of water level. Other interested state agencies will be provided notice of the filing and the scheduling of the field visit. At the request of an applicant, the Department may conduct field evaluations sufficient to determine an Alternative Water Flow or Alternative Water Level.
- C. The Department shall maintain and make available all Alternative Water Flows or Alternative Water Levels. An Alternative Water Flow or Alternative Water Level shall remain in effect until such time as a new Alternative Water Flow or Alternative Water Level is established by the Commissioner or a regulatory permit, as provided in Section 8, is issued.

8. Flows or water levels established by regulatory permit or water level order

- A. **Flows and water levels not related to hydropower projects.** Flows or water levels may be established as part of any regulatory permit or water level order issued by the Department, the Land Use Regulation Commission, or as authorized by the Cobbossee Watershed District. Flows or water levels established by regulatory permit shall be based on the results of a site-specific flow or water level study, taking into account the need for natural variation of flow and natural variation of water level. Where an existing regulatory permit issued by the Department or the Land Use Regulation Commission establishes flows or water levels prior to the effective date of this chapter, those flows or levels shall continue for the effective period of the permit. In-stream flow and water level requirements in this chapter apply to any subsequent reissuance of a

regulatory permit by the Department or the Land Use Regulation Commission. Amendments or modifications to an existing permit which do not alter the manner of use or the amount of the water withdrawal, as stated in the permit, shall not require review under this chapter. A schedule may be assigned in any reissuance of a regulatory permit that will provide a reasonable period of time for compliance with a new flow or water level requirement. In a watershed where flows or water levels have been established by a regulatory permit of the Department or the Land Use Regulation Commission, those flows or levels must be taken into account when calculating downstream flows or levels in accordance with section 7 above, during the effective term of the permit.

B. Hydropower Projects. Flows and water levels for hydropower projects, as defined in 38 M.R.S.A. §632(3) shall be established through the Water Quality Certification process pursuant to Section 401 of the Clean Water Act, 33 U.S.C. §1341, or a permit issued pursuant to the Maine Waterway Development and Conservation Act, 38 M.R.S.A. §630 et seq., and therefore shall not be subject to or established through this Chapter, notwithstanding any other provision in this Chapter

9. Drought flow variance for Community Water Systems. Whenever natural drought conditions, in combination with Community Water System use, cause the applicable instream flow or water level requirements of this chapter to not be maintained, the Community Water System may continue to withdraw water for public need subject to any conditions the Department may impose through the issuance of a variance pursuant to 40 CFR 131.13 (2006). Such variances may last for the duration of the drought condition and shall protect all water quality standards to the extent possible, recognizing the combined effects of a natural drought and the need to provide a safe, dependable public source of water.

10. Implementation of water flow and water level requirements

A. Implementation of water flow and water level requirements for existing agricultural producers. An existing agricultural producer, as defined in Title 7 §353.2.A or §353.2.B, has 5 years from the effective date of this chapter to attain the applicable in-stream flow and water level requirements established in sections 4, 5, 6 or 7 of this chapter. An existing agricultural producer who has, or whose predecessor had, a permit or a written voluntary agreement establishing withdrawal limits must adhere to those limits for the 5-year period or until in compliance with the requirements established in this chapter. The Commissioner, upon recommendation of the Maine Agriculture Water Management Board, may grant an extension of the implementation period beyond the original 5 years for an agricultural producer who qualifies for the 5-year compliance period, if the Department determines that one or more of the conditions for a compliance extension established in Title 7 §353.4 apply.

B. Implementation of water flow and water level requirements for existing Community Water Systems. An existing Community Water System has five years from the date it is notified by the Department of non-compliance with the instream flow or water level requirements of this chapter to obtain a Community Water System Withdrawal Certificate from the Department and to enter into an agreement to take all feasible actions necessary to comply with, or restore to the extent feasible, the applicable in-stream flow and water level requirements established in sections 4, 5, 6 or 7 of this chapter for the source waterbody and affected downstream waters. The Commissioner may grant an extension of this 5-year implementation period if it can be demonstrated that reasonable progress toward implementation of a Community Water System Withdrawal Certificate has occurred.

11. **Watersheds most at risk from cumulative water use.** Waters which do not meet one or more water quality standard due, in whole or in part, to the impact of water withdrawals are determined to be most at risk from cumulative water use. Additionally, the following waters identified in paragraphs A, B, and C below are determined to be most at risk.
- A. **Class AA river or stream watersheds most at risk from cumulative water use.** Watersheds which have direct withdrawal capacity that collectively amounts to 10% or more of any seasonal median flow for the season that withdrawal is intended.
 - B. **Class A, B, or C river or stream watersheds most at risk from cumulative water use.** Watersheds which have direct withdrawal capacity that collectively amounts to 50% or more of any seasonal median flow that withdrawal is intended.
 - C. **Class GPA waters most at risk from cumulative water use.** Waters which have direct withdrawal capacity that collectively amounts to 80% or more of the available water for any defined period as provided by the standard allowable alteration.
 - D. This definition does not constitute a regulatory standard and is not intended as such. It is only intended to identify watersheds that are most at risk from cumulative water use for the purpose of directing future efforts to address water use planning.
12. **New activities in state waters.** Any activity altering the flow or water level of classified state waters that requires a new or reissued regulatory permit from the Department or the Land Use Regulation Commission, as of the effective date of this chapter, will be regulated according to the flow and water level requirements in this

chapter. An Alternative Water Flow or Alternative Water Level may be incorporated in any new or reissued regulatory permit.

13. **Certain activities prohibited in Class AA waters.** Any activity in Class AA water that causes an alteration from the naturally occurring flow must protect all water quality standards, including the free-flowing characteristic. In-stream dams or other permanent alterations of the natural stream channel are prohibited. Activities, including the construction of structures in or adjacent to a waterbody to provide water withdrawal, or temporary diversions necessary as part of approved construction activity, may be permitted according to provisions in the Natural Resources Protection Act (38 M.R.S.A. Section 480).

14. **Legal Water Rights Not Affected.** Determinations under this chapter do not confer legal water rights or constitute a determination of reasonableness of use with respect to other existing or future water users

STATUTORY AUTHORITY: 38 M.R.S.A. §470-H

EFFECTIVE DATE:

August 24, 2007 - filing 2007-306

APPENDIX C
SUPPLEMENTAL MATERIAL FOR CHAPTER 3

C.1 Streamflow Trends in Maine

Daily streamflow trends were assessed for the 13 unregulated gaged streams in Maine from 1950-2016. Daily data were obtained from USGS and were smoothed using a 3-day average. Both the mean and median trends were calculated. Both are measures of central tendency, but the median is robust to outliers making it a more reasonable estimate of change (Koenker, 2017). The mean and median trend are broadly agreeable with significant decreasing trends shown in the late spring / early summer period over northern Maine and increasing streamflow trends in winter and early to mid-spring. The median shows negative trends earlier in the spring in the southern and coastal part of the state while the mean detects no significant trend.

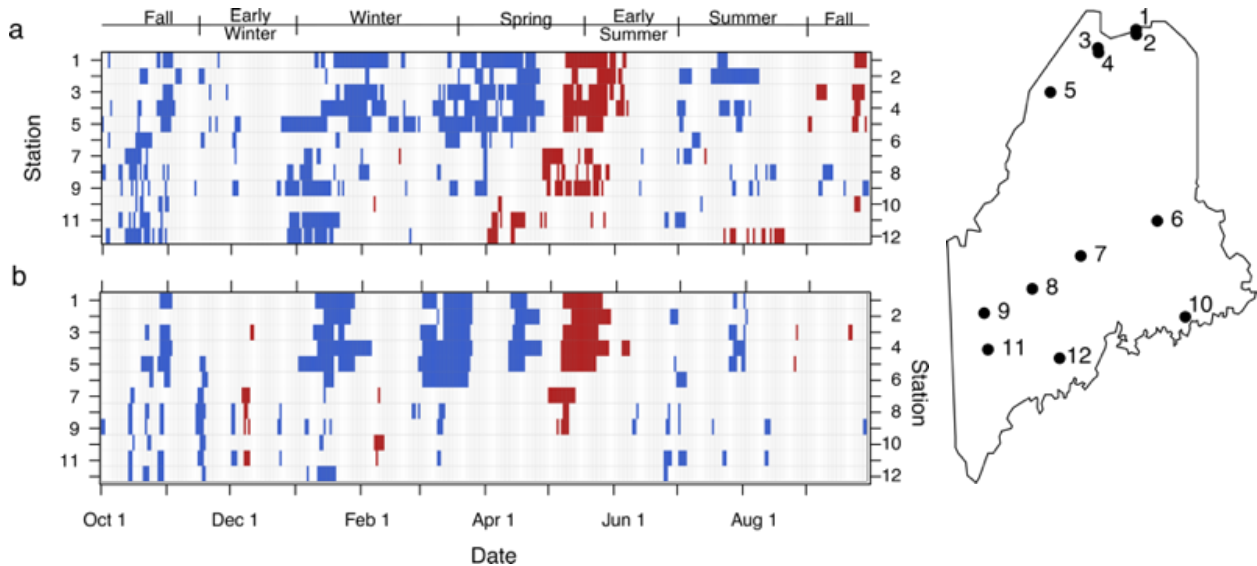


Figure C.1: Historical streamflow trends (1950-2016) for unregulated Maine streams. a) median and b) mean. Positive trends shown in blue and negative in red. All trends significant at $\alpha = 0.05$ and calculated for a 3-day moving average window. Seasonal delineations according to Ch. 587 shown above. Median trend significance assessed by wild bootstrap (Feng, 2011)

C.2 Stages of Rulemaking in Maine

Rule Proposal. In Maine, all rules are denoted as either ‘routine and technical’ or ‘major substantive’ by the State Legislature. While ‘routine and technical’ status gives the rulemaking entity considerable discretion in content, ‘major substantive’ rules are subject to final approval by the Legislature, which can impose limitations on the scope of the resulting rule. The public may also propose rules through petition. Prior to the 1995 update to the APA, all rules were treated as ‘routine and technical’ rules.

Draft Development. Once a rule is authorized by statute, drafts are developed by the agency. Selected parties may be invited to lend input or expertise to the draft. Participation at this stage is accessible only by invitation from the agency, but has been found to have a higher influence on the rule content in other states and at the federal level than at later stages in the processes (Rinfret, 2011; Rinfret et al., 2014). Drafts may undergo multiple iterations during agency or inter-agency review and may often involve coordination with other state and federal agencies for data, support, and compliance. For example, the Maine Department of Environmental Protection (DEP) may coordinate with the U.S. Environmental Protection Agency (EPA) to ensure compliance with existing federal water quality regulations. When a draft is approved by the agency commissioner, it is reviewed and approved by both the Governor and Attorney General’s offices.

Public Comment. A public notice of rulemaking is issued, and members of the public have the opportunity to view and submit comments on the draft rule. Hearings are automatically held for ‘major substantive’ rules but may be requested by the public for other rules. The agency must respond to all comments in writing and may make changes based on input. If the changes to the rule are significant, then the rule may be subject to another round of public comment. If a rule is further designated by the legislature to be an emergency rule, the public comment period may be limited in scope or absent due to time constraints.

Review and Approval. ‘Routine and technical’ rules are then approved by the agency commissioner and approved by the Attorney General’s Office before going into effect. ‘Major substantive’ rules are approved by the commissioner, any agency decision boards, and then by the legislature. The legislature may hold hearings, request additional information from other agencies, and mandate revision. As the legislature is comprised of elected representatives, this presents another opportunity for groups or individuals to lobby for the approval or rejection of rules. Stakeholders with greater leverage due to economic importance may be more influential at this stage (Crow et al., 2017). If not approved, the rule is returned to the agency for revision. After any rule or law is filed with the Attorney General’s Office, it may be subject to review if challenged in court.

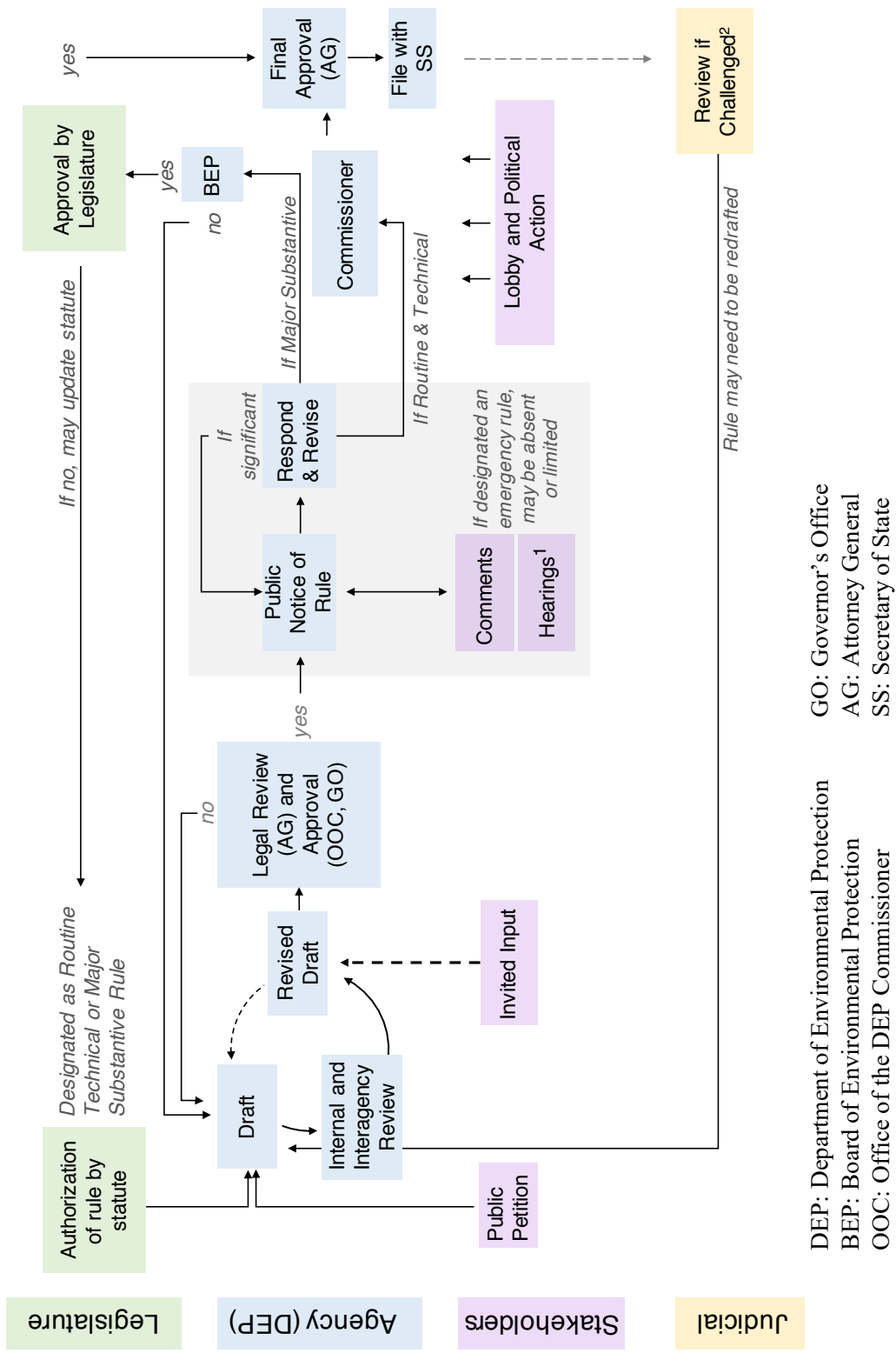


Figure C.2: Rulemaking process in Maine. All elements are derived from the State Administrative Procedures Act. ¹Hearings are required for all major substantive rules, but otherwise may be requested by members of the public. ²Any law or rule could be subject to potential legal challenges.

Table C.1 Key events in Maine Chapter 587 Rulemaking

1998	•	DEP drafts modifications to Chapter 581: Regulations Relating to Water Quality Evaluations to include flow rules
1999	•	DEP drafts Chapter 587: In-stream Flow and Lake and Pond Water Levels
1999-2000	•	DEP revises draft internally and with selected stakeholders
2002	•	Water Withdrawal Reporting Program enacted in 38 M.R.S.A. §470-A-G. §470-E authorizes adoption in-stream flow rules by Jan 1, 2005. Designated as a major substantive rule.
Mar. 2005	•	Proposed rule presented to legislature. Delayed to next session.
Jun. 2005	•	Legislature re-authorizes DEP to pursue in-stream flow standards by §470-H. (LD 1588, HP 1124)
Apr. 2006	•	Agricultural producers are given a 5-year extension to comply with flow-rules when adopted provided they work with the Agricultural Management Board on alternative solutions (LD 1776, SP 693).
Apr. 2006	•	Legislature directs DEP to work with stakeholders to resolve conflicting water uses. In-stream flow rules requested by Jan 1, 2007 (LD 2070, SP 809)
Jun. 2006	•	Public notice of proposed Ch. 587 issued
Aug. 2006	•	Maine Rural Water Association petitions Public Utility Commission (PUC) to investigate how the proposed rule will impact water rates and services.
Nov. 2006	•	PUC opens inquiry. Invites comments from stakeholders.
Dec. 2006	•	Maine Rural Water Association (MRWA) issues report on fiscal impact of Ch. 587.
Feb. 2007	•	PUC issues initial report for public comment
Mar. 2007	•	PUC final report is released. Concludes that Ch. 587 places no financial burden on municipalities.
Apr. 2007	•	Bill introduced to include a mechanism in proposed rule to deal with conflicts between drinking water and aquatic needs. Failure to pass out of committee (LD 1359, SP 473)
Jun. 2007	•	§470-H amended to include coordination among DEP, Drinking Water Program of the Department of Health and Human Services and PUC in implementing rules pertaining to public water systems (LD 968 HP 728).
Jun. 2007	•	Ch. 587 approved by legislature as an emergency order (LD 968 HP 728).
Aug. 2007	•	Ch. 587 effective
May 2011	•	Bill exempts agricultural users who comply with Ch. 587 from reporting water use under the Water Use Reporting Program (38 M.R.S.A §470-C; LD 1015 HP 751).

Table C.2: Selected Environmental Flow Assessment Approaches

Approach	Description	Benefits	Shortcomings	Example
Tennant Method	Percentage of mean annual flow left in stream relating to fish-habitat conditions. Percentage varies by season.	Can include different standards based on seasonality	Moderate data requirements, based on fish habitat, lack of seasonal variability	Tennant (1976)
Flow Duration Curve	Requires percentile of average annual flows to be maintained for specific ecosystem functions	Modifiable for any ecological process, can include flows of any volume or frequency	Based on salmonid habitat, lack of transferability	UK Environment Agency
7Q10	7 Day low flow that occurs on average every 10 years. (Example of flow duration curve)	Low data requirements.	Not based on biological criteria. Only protects for lowest flows. Intended to be a water quality standard.	Aroostook Water and Soil Management Board (1996)
Wetted Perimeter	Measures flow at transects along a river location. Standard determined to keep percentage of the bankfull habitat wet	Can be modified to add multiple transects, relatively simple method	Tends to focus on single habitat with assumption other habitats will respond positively. No seasonable variation.	Nelson (1984), Gippel & Stewardson (1998)
:	:	:	:	:

Table C.2: Selected Environmental Flow Assessment Approaches (Continued)

Approach	Description	Benefits	Shortcomings	Example
Seasonal Aquatic Baseflow	Assigns values of 0.5, 1.0, and 4.0 cubic feet per square mile as seasonal standard, or from flow data	Easy to implement, seasonal variation	Peak flow events not maintained. May be inappropriate when transferred to other contexts	USFWS New England Flow Policy (1981)
Range of Variability Approach	Calculates hydrological indices using daily-flow records and identifies natural ranges for an ecological setting	Can be used to estimate standards for streams a similar type.	Allowable alteration can be difficult to determine	Richter et al. (1996)
Instream Flow Incremental Methodology	Hydrologic modeling procedure developed to predict habitat suitability for a target species	Comprehensive flow-habitat relationship, ability to model scenarios, habitat conditions can be modeled over time	Data and time intensive, optimized for a specific species	US Fish and Wildlife Service (1980s)
Building Block Methodology	Bottom-up approach to build flow regime for wet and dry years based on flows critical to ecological health	Involves stakeholders, forward looking, can be combined with other methods	Data and time intensive, lack of guidelines for stakeholder process	King & Louw (1998)
:	:	:	:	:

Table C.2: Selected Environmental Flow Assessment Approaches (Continued)

Approach	Description	Benefits	Shortcomings	Example
Downstream Response to Imposed Flow Transformations (DRIFT)	Model based software to assess present conditions and response to alteration. Combines economic, social, and ecological considerations to make flow recommendations	Can be used with limited field data.	Time intensive	King & Brown (2006)
Ecological Limits of Hydrologic Alteration (ELOHA)	Uses hydrologic indicators to develop relationships between ecosystem characteristics and flow. Uses stakeholder process to determine flow recommendations.	Adaptable, stakeholder participation, monitoring and adaptive management approach, iterative process for use with incomplete data	Time intensive, challenges in coordinating stakeholders and decision-makers, long-term commitment and funding for monitoring	Finn and Jackson (2011)

Table C.3: Characteristics of USGS Flow Equation Reports for Maine

Report	Location	Statistic	Recommended Basin Size
Lombard et al. (2003)	Eastern Aroostook County	August Median	0 – 10mi ²
Dudley (2004)	Statewide	Monthly Median	10 – 15,000mi ²
Lombard (2004a)	Eastern Coastal Maine	August Median	0 – 10mi ²
Lombard (2010)	Southern Maine	June and August Median	0 – 10mi ²

APPENDIX D

SUPPLEMENTAL MATERIAL FOR CHAPTER 4

D.1 Global River Basin Scale Precipitation

Monthly total precipitation grids were summed from June – May at each grid point, producing annual precipitation grids for 1951 – 2011 where the total for the 1951 year is June 1951 – May 1952. A June – May year was used to better preserve wet and dry seasons globally. For example, many basins in the Southern Hemisphere have the highest percentage of annual precipitation contributed in the November – March period, which would not be captured using a calendar designation (Figure D.1). For example, the Zambezi basin in southern Africa receives the majority of its annual precipitation December – February. Aggregation of data over a calendar year would split the primary wet season for this basin between two years. A June – May year also largely captures the monsoonal season precipitation for Southeast Asia. Precipitation grids were weighted by $\sqrt{|\cos(\text{latitude})|}$ to account for for unequal areal extent of grid points in various latitudinal zones (Chung and Nigam, 1999). The weighting was found to have a negligible effect on precipitation totals as compared to simple areal averaging. Annual precipitation grids were areal-averaged over the basin delineations to produce annual totals on the basin-scale. Monthly SST grids were averaged in the same June – May period, producing annual average SST grids. From the standpoint of SST variability, the June to May period affords a clearer expression of El Niño and La Niña events, given their emergence in late boreal summer, peak anomalies during the winter and dissipation during the early spring season.



Figure D.1: River basins from “405 major water basins of the world” obtained from the Global Runoff Data Centre (GRDC) used in analyses.

D.2 Spatial and Temporal Variability of Global Precipitation and Sea-Surface Temperature

Dimensional reduction using Empirical Orthogonal Function (EOF) analysis was conducted on both SST and precipitation to assess the level of correlation between the leading patterns of SST and precipitation variability. A key feature of EOFs is that it reduces information into leading patterns of variability, and the patterns are uncorrelated (Jolliffe, 2002). This allows EOFs to be used as regression covariates without the risk of multicollinearities.

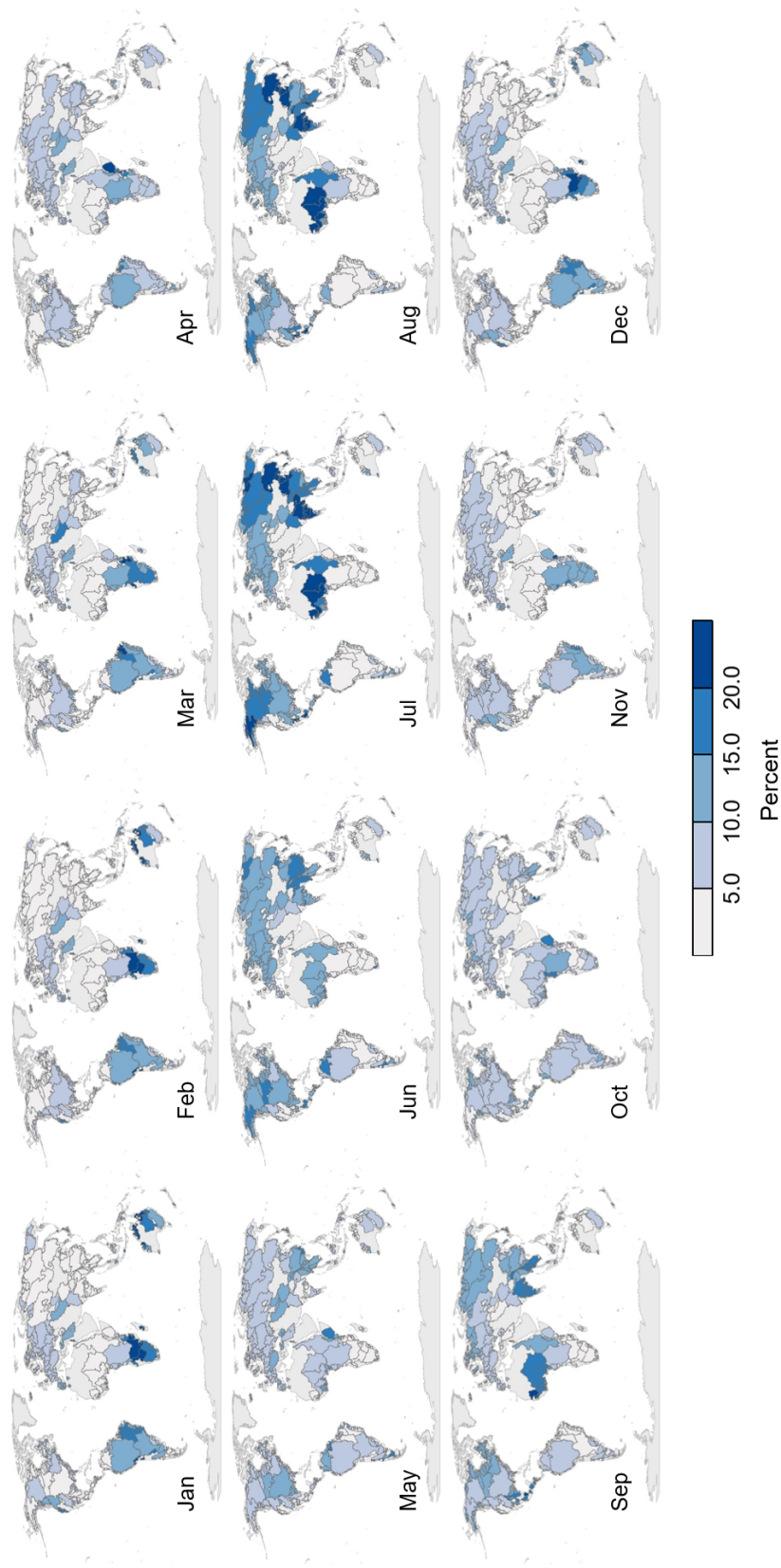


Figure D.2: Average percentage of annual precipitation (1951 – 2011) occurring in each month.

Table D.1: Pearson Correlation Coefficient of Precipitation and SST EOFs

SST	Precipitation				
	EOF1	EOF2	EOF3	EOF4	VE (%)
EOF1	0.92	0.00	0.13	0.02	33.10
EOF2	0.01	0.40	0.17	0.18	10.30
EOF3	0.03	0.32	0.36	0.09	6.30
EOF4	0.19	0.04	0.08	0.37	4.60
VE (%)	15.64	5.30	4.02	3.78	

D.2.1 Sea-Surface Temperature Patterns

Modes of variation in the north Pacific appear in both EOF1 and EOF2. The pattern of variation in the north Pacific appearing in EOF1 and EOF2 is consistent with the Pacific Decadal Oscillation [PDO; (Gu and Adler, 2015)]. PDO has a similar spatial pattern of SST anomalies to ENSO, but has different relative amplitudes between the north and tropical Pacific, and lower amplitudes than ENSO in the eastern equatorial Pacific (Deser et al., 2010)

The variation linked to the PDO pattern is partitioned between EOF1 and EOF2, with phase and magnitude influenced by the ENSO signal (Newman et al., 2003). The PDO index has a correlation coefficient of 0.7 with EOF1, and -0.3 with EOF2. While EOF1 and EOF2 most closely correlate with ENSO and AMO and are used as proxies in the study, it is acknowledged that PDO as well as other measures of SST variability contribute to these empirically-derived modes and engender shifts in the precipitation distribution.

D.2.2 Precipitation Patterns of Variability

The long-term annual precipitation mean for 1951-2011 shows low precipitation over Northern Africa, western United States, the west coast of South America, central Asia, and central Australia (Figure D.3a). Higher precipitation amounts are seen over the tropics, the Eastern US, and Europe. The trend in the median is explored as the median is robust to outliers (Figure D.3b). Trends show decreases over Africa, the west coast of the United

States, and parts of southeast Asia, and increases in North America, South America, Australia, and Europe. The Median Absolute Deviation (MAD) statistic is used as a robust measure of variability, as standard deviation may be influenced by outliers (Hogg, 1979). The MAD statistic shows highest levels of variability

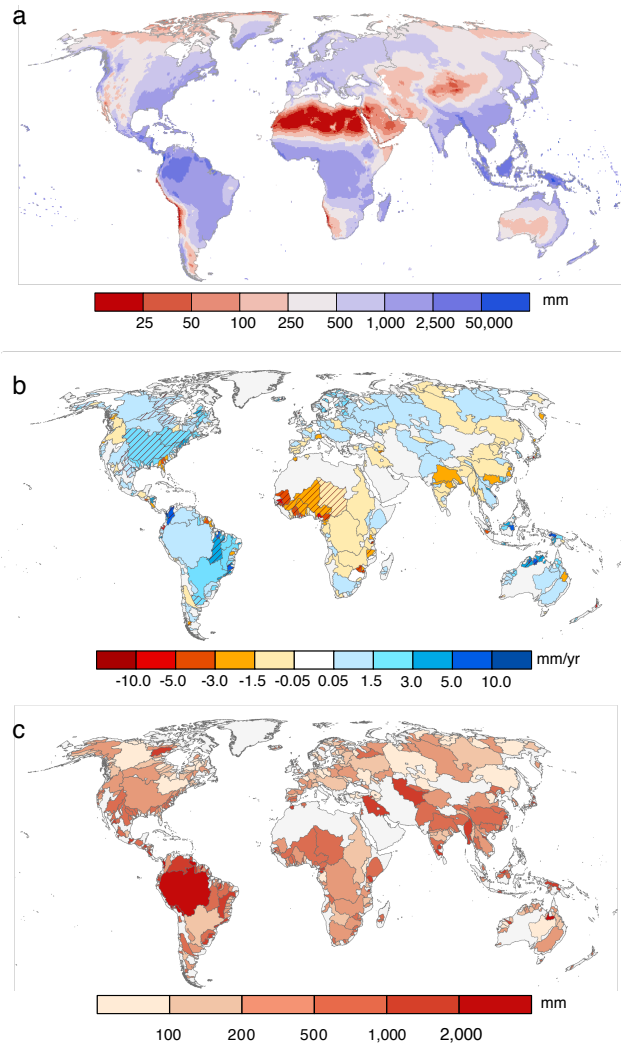


Figure D.3: Global patterns of total annual precipitation weighted by latitude. a) mean annual precipitation (mm) 1951-2011, b) median trend (mm/year) for 1951-2011. Cross-hatch indicates significance at $\alpha = 0.1$. c) Median Absolute Deviation (MAD) for 1951-2011.

over Southeast Asia, the Indian subcontinent, Northern and coastal South Africa, and parts of Europe and North America (Figure D.3c). Lowest inter-annual variability is seen over Northern Africa, central Asia, and generally in Northern latitudes.

D.3 Changing Perspectives of Conditional Risk: Worked Example

A comparison of exceedance probabilities produced by LR and QR demonstrates the tendency for LR to over or underestimate changes in the tails of the probability distribution function (PDF) representing excesses and deficits. Figure D.4 compares the PDFs for QR and LR generated at 1951, 1981, and 2006, for a case where there is a significant decrease in $\tau = 0.8$ and increase in $\tau = 0.2$ conditioned on the years 1951 – 2011. The trend in the mean is positive, with LR implying that the entire PDF undergoes a location shift with the mean. Using the unconditional $\tau = 0.2$ and $\tau = 0.8$ quantiles as thresholds, Table D.2 shows the percent change in non-exceedance probability for $\tau = 0.2$ and exceedance probability for $\tau = 0.8$. While QR shows a decrease in both the probability of high and low annual totals over time, LR predicts an increase in probability of a high annual total. For example, for 2006 the probability of exceeding the threshold value is 37.48% less than what is implied by LR. Furthermore, QR implies reduced variability over time, while it is time-invariant for LR.

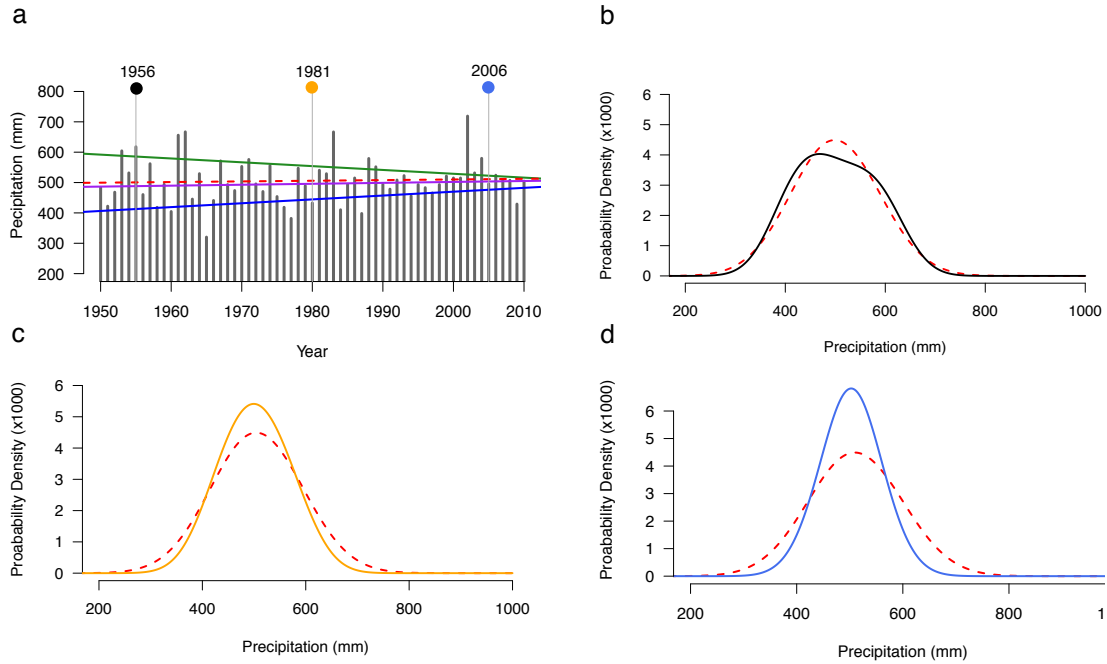


Figure D.4: Comparison of changes implied by QR and LR for synthetic data. Empirical probability distributions were constructed for years marked by gray lines. Distributions were conditioned on the year covariate only for illustrative purposes. Solid and dashed lines correspond to QR and LR distributions respectively for b) 1956, c) 1981, and d) 2006.

Table D.2: Change in Probability Across Selected Quantiles Over Time

$\tau = 0.2$ threshold: 434.56mm				
	1956	1981	2006	Difference (1956-2006)
QR	0.25	0.18	0.13	-48.58 %
LR	0.23	0.21	0.19	-15.22 %
Difference	6.80%	-17.88 %	-53.50 %	
$\tau = 0.8$ threshold: 573.12mm				
QR	0.23	0.16	0.11	-49.78 %
LR	0.21	0.22	0.24	16.50 %
Difference	8.40%	-38.50 %	-112.40 %	

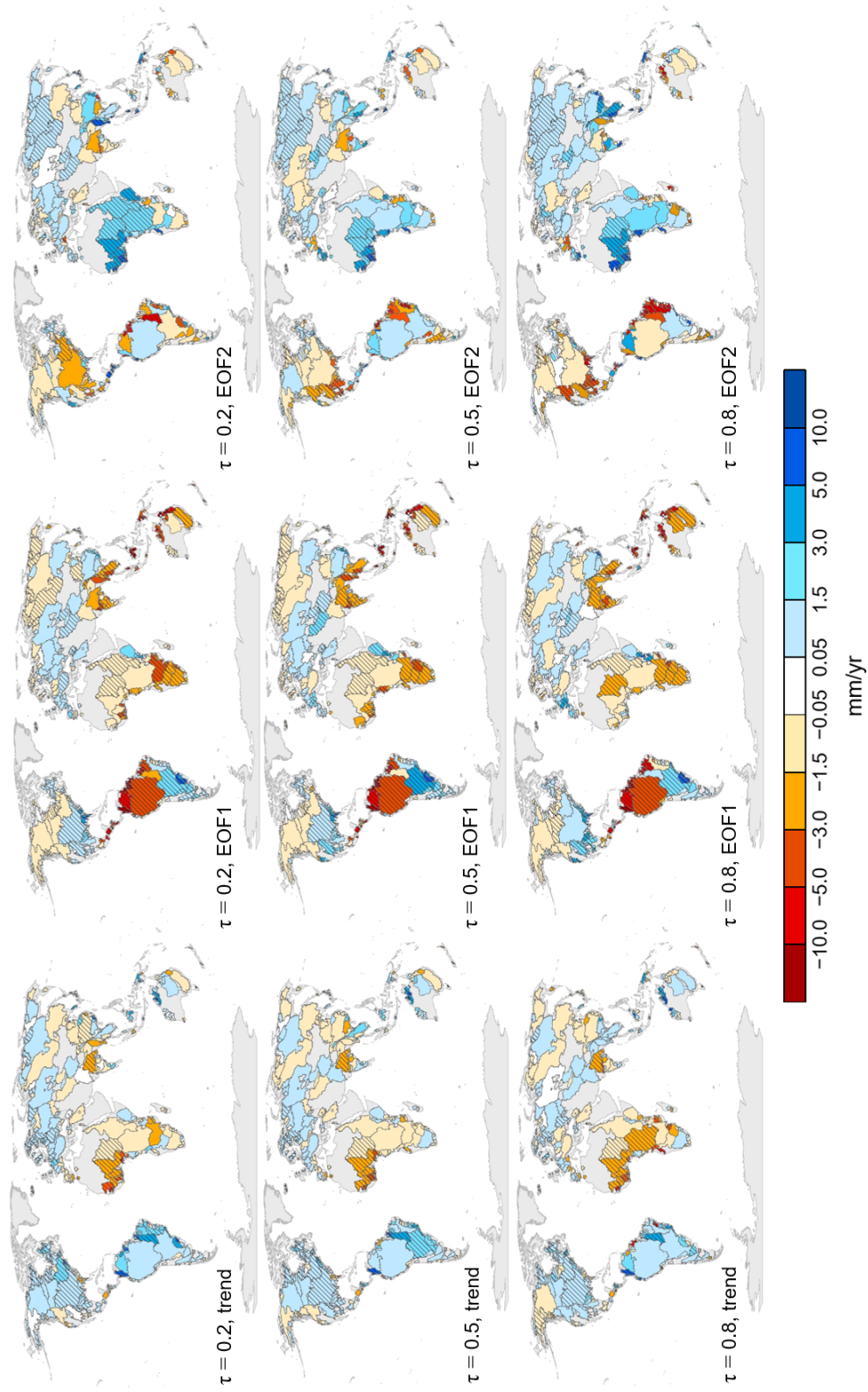


Figure D.5: Spatial distribution of weighted basin-level precipitation response. Response is conditioned on year, EOF1, and EOF2 based on the $\tau = 0.2$, 0.5, and 0.8 quantiles of basin areal average annual precipitation 1951 – 2011. Cross-hatch represents significance at $\alpha = 0.1$.

APPENDIX E
QUANTILE-SPECIFIC PRECIPITATION RESPONSES TO SST
VARIABILITY ON CONTINENTAL SCALES

Risk can be characterized by the combination of exposure and vulnerability.

Quantile-specific SST responses indicate increased or decreased probability of excesses and deficits as well as changes in variability. However, there are a host of non-climatic factors such as population, infrastructure, governance, dominant sectors, and the use of surface versus groundwater sources that influence the level of vulnerability a basin has to climatic impacts. A continental-scale discussion of quantile-specific changes and factors influencing vulnerability in example basins is presented.

E.0.1 Africa

The African continent has the most basins that show sensitivities across quantiles to all covariates. 51% of basin land area in Africa shows either one or multiple quantiles with opposite responses in EOF1 and EOF2, with EOF1 largely associated with decreases and EOF2 increases. Other studies have shown influences of ENSO on precipitation in Eastern and southern Africa, and AMO in northern Africa (Knight et al., 2006; Dai and Wigley, 2000). When EOF1 and EOF2 are in the same phase, shifts are tempered, and when they are different shifts are magnified. For example, the Pangani basin in Tanzania is one of the most sensitive basins to EOF1 with coefficients of 4.11 mm/°C and 6.17 mm/°C for the $\tau = 0.2$ $\tau = 0.8$ quantiles (Table E.1). Shifts in the extremas conditioned on EOF2 are not significant for this basin. Given changes in phase and magnitude of EOF1, the shifts in Pangani can be dramatic and are asymmetric. Due to the asymmetry, there is also high interannual variability when EOF1 magnitudes are large. The Pangani basin has experienced high levels of population growth, and therefore water demand, coinciding with water conflict issues between small-scale and industrial-scale agriculture irrigation projects

and hydropower (Mbonile, 2005). It is also coincident with one of the most water-stressed aquifers in Tanzania with demand exceeding recharge (Richey et al., 2015). With a population of over 3.7 million residing in the basin, changes in global ocean state as characterized by EOF1 could threaten the social, economic, and food security of the population. The neighboring Tana basin in Kenya is characterized by similar sensitivities in $\tau = 0.2$ and $\tau = 0.8$ and is sensitive to EOF2 in the 20th quantile 4.62 mm/°C. Depending on phase and magnitude of EOF1 and EOF2, the change in $\tau = 0.2$ can be magnified or tempered. For example, in west Africa, the Niger basin is sensitive to both EOF1 and EOF2, with opposite coefficient sensitivities in $\tau = 0.8$ (−1.08 mm/°C, 3.13 mm/°C for EOF1 and EOF2 respectively). When EOF1 and EOF2 are in opposite phases the probability of extreme wet conditions and variability is higher than when in the same phase. The Niger basin has high population concentration, spans 9 out of the world's 30 poorest countries, with agriculture as the most dominant use (Ogilvie et al., 2010). Rainfed agriculture in particular is highly sensitive to the spatial and temporal variability of precipitation, with excesses and deficits of concern both inter- and intra-annually. Furthermore, the basin intersects with the Taoudeni aquifer which has one of the smallest mean annual recharge rates (Richey et al., 2015). Coupled with high demand and low recharge, it is considered a water-stressed aquifer. Other basins showing high sensitivity to EOF1 and EOF2 conditions include the Chad River Basin, Sassandra Basin, Gambia Basin, and Volta Basin in Western Africa. While some basins have higher sensitivity than others, the features of the countries within those basins such as infrastructure, groundwater versus surface water reliance, population, socio-economic factors, and governance structure will affect the capacity for adapting to these changes as well as the magnitude and types of impacts produced by extreme events (Green et al., 2015b). For example, the Congo basin has low magnitude sensitivity across the distribution with a significant increase in the $\tau = 0.2$ for positive EOF2. While the Congo basin water extractions are low, populations are at risk for scarcity due to low infrastructural development, access to safe drinking

water, and governance challenges (UNEP, 2011), demonstrating how vulnerability to water-related risks can be significantly influenced by non-climatic factors.

E.0.2 Australia and Southeast Asia

The Australian and Southeast Asian basins show examples of sensitivities across all quantiles to covariates, but particularly to EOF1. Studies have shown sensitivities of precipitation in Australia to ENSO along with other climatic modes of variability (Power et al., 1999; Cai et al., 2011; Min et al., 2013). In Australia, the Blackwood and Murray basins show the highest magnitude of sensitivity to EOF1 and EOF2 conditions. The Blackwood basin is the largest southwestern basin with an area of 23,500km². Agriculture is the predominant land use, with wheat crops replacing native deep-root vegetation leading to both a rise in the water table and salinization of ground and surface water resources (Hodgson et al., 2004). Land-use changes and changing climatic conditions have led to a decrease in biodiversity of the region, threatening endemic species (Horwitz et al., 2008). While drainage solutions have been explored, it is predicted that increases in rainfall could lead to higher recharge and increased salinity in the short-term (Ali et al., 2010). Significant decreases are found in $\tau = 0.8$ for EOF2 ($-4.67 \text{ mm}/^{\circ}\text{C}$) $\tau = 0.2$ for EOF1 ($-1.40 \text{ mm}/^{\circ}\text{C}$). Significant sensitivity captured by trend also shows precipitation decreases. However, depending on EOF1 and EOF2 conditions, this basin could experience a higher probability of precipitation increase, as well as an increase in variability due to asymmetries in $\tau = 0.2$ and 0.8 response. The Murray basin shows similar sensitivities to EOF1 with decreases in both $\tau = 0.2$ and 0.8 . Water resources are over-extracted due to irrigation, mining, and other uses, with insufficient supply to address environmental and human requirements. Irrigation for agriculture is the primary user, with 70% of sustainable yields from the aquifers dedicated to those uses (Merz, 2003). Drier conditions are more likely under positive EOF1 conditions (responses for $\tau = 0.2$ and $\tau = 0.8$ are $-2.44 \text{ mm}/^{\circ}\text{C}$ and $-2.98 \text{ mm}/^{\circ}\text{C}$ respectively), exacerbating existing issues.

Basins in southeast Asia show relatively higher magnitudes of sensitivity, with precipitation in the Pahang, Kelantan, and Kinabatangan basins in Malaysia sensitive primarily to EOF1. Malaysia has an abundance of water resources, but has become stressed due to increases in urban population, high demand, poor infrastructure, and inefficient use of resources (Ti and Facon, 2001). For example, irrigation uses approximately 68% of total water consumption but with efficiencies of only 40-50%. All three basins show significant decreases in $\tau = 0.2, 0.8$, with the Kinabatangan having a coefficient of $-20.10 \text{ mm}/^\circ\text{C}$. It is important to note that while SST variation influences precipitation, water resources are sensitive to temperature as well, with temperature contributing to drought through increased evaporation rates in this region (Dai, 2012). Recent headway has been made in rainwater harvesting as one method to combat water shortages (Lee et al., 2016).

E.0.3 Asia

The Southern Asian and Indian subcontinent broadly show negative (positive) responses to EOF1 (EOF2). Studies have suggested an influence of both ENSO and AMO on precipitation in this region, particularly during the summer monsoon (Ju and Slingo, 1995; Goswami et al., 2006; Annamalai et al., 2007). The Ganges and Indus river basins are both highly populated with similar characteristics. The Ganges shows decrease in $\tau = 0.8$ for EOF1 ($-2.64 \text{ mm}/^\circ\text{C}$), indicating decreased probability of wet events. The basin is situated within 4 countries, and has an imbalance between supply and demand partly due to the seasonal distribution of annual precipitation. Irrigation-based upstream diversion of flows to ecologically important sites including the Sundarban mangrove ecosystem, has led to increased saline levels and altered sediment deposition (Gopal and Chauhan, 2006). The groundwater systems are also stressed due to extractions exceeding recharge rates (Richey et al., 2015). The neighboring Indus basin shares similar challenges with stressed surface and groundwater resources due to high demand, population increase, irrigated agriculture, and diversions for hydroelectric power systems (FAO, 2011). Population growth has

contributed to the overuse of groundwater in the Pakistani part of the basin in particular (Qureshi et al., 2010). Coupled with high demand and shrinking resources, additional stress by changes in precipitation could exacerbate existing issues. Further East, the Mekong shows a decrease in both $\tau = 0.2, 0.8$ to EOF1 as well as an increase with EOF2 (4.72 mm/°C), with vulnerabilities evident with both excesses and deficits for this system. The basin spans 6 countries supporting 70 million people largely in rural areas. Due lack of infrastructure and reliance on the river for subsistence, the population is vulnerable to degradation and shocks (FAO, 2011b). Diversion of water for agriculture, land-use change, and climate variability has made many endemic species vulnerable, with an overall loss of biodiversity (Ngamsiri et al., 2007). Groundwater aquifers are largely recharged by annual flooding, but locally may experience stress (Wagner et al., 2012). The Huang He (Yellow River) basin shows similar sensitivities with decrease in the $\tau = 0.2$ for EOF1 (−1.42 mm/°C). High population density with high water use for irrigation has contributed to demand exceeding supply (Zhu et al., 2003). In past years, the river has run dry before reaching the outlet, and typically only 10% of flows reach the sea. Frequent flooding and droughts make this region susceptible to both human and ecological risk (Gassert et al., 2013; Pietz, 2015). The neighboring Yangtze basin has more supply than the Yellow River but faces similar growing demand issues, particularly as inter-basin transfers are initiated. The Dongjiang river basin in Southern China shows similar challenges, characterized by a significant decrease in $\tau = 0.2$ conditioned on EOF1 (−1.42 mm/°C). The basin provides 80% of Hong Kong’s annual water demands, with potential deficits likely to impact a major urban area.

E.0.4 Europe

Compared to other regions, few western European basins show significant precipitation response to EOF1 and EOF2. Europe sees a summer season sensitivity to AMO (Sutton and Hodson, 2005; Knight et al., 2006) with studies showing a relationship primarily winter

to ENSO (Mathieu et al., 2004; Brönnimann, 2007). Other global scale analyses show precipitation increases annually with ENSO, with increases in winter (Dai and Wigley, 2000; Sun et al., 2015). For example, the Garonne, Seine, and the Rhone basins in France all show positive sensitivity to EOF1 in $\tau = 0.8$. The Garonne has the largest supply to demand deficit in the country, with 70% of total flow during low-flow periods allocated for irrigation (Martin et al., 2016). Moreover, the basin is considered at moderate risk for not meeting set ecological and quality standards by the European Union's Water Framework Directive (WFD) (Barraqué et al., 2010). The basin shows sensitivity in $\tau = 0.2$ to EOF1 (1.85 mm/°C) indicating that lower annual precipitation is more likely under negative EOF1 conditions, exacerbating supply issues. Similarly, the nearby Seine has high extraction levels, with 93% of agricultural and 59% of municipal demand met from groundwater extractions from the Genevese aquifer. Potential decreases in precipitation coupled with increasing demand diminishes recharge, which also can impact ecological systems. In the 1990s, severe drought conditions caused aquifer-fed rivers in the Loire basin to run dry, with detrimental impacts for riverine ecosystems. Similar issues face the Guadalquivir basin in Spain (Dumont et al., 2013), however sensitivity to EOF2 in $\tau = 0.8$ (8.77 mm/°C) indicates a higher probability of precipitation increase compared with other basins in the region under positive EOF2 conditions. A key ecological example comes from the Danube basin, whereby only low magnitude response is seen in $\tau = 0.2$ to EOF1. Approximately 85 million people spanning 19 countries live in the basin, with agriculture, industry, municipal, and hydropower being key uses. The flow of the Danube has been highly altered by a series of dams and other infrastructure projects for hydropower generation and flood protection (UNESCO, 2005). Furthermore, 15,000 to 20,000 km² of floodplains have been cut off from the river, with flooding a concern for high population centers along the river (Schober et al., 2015). Flow alteration and development along floodplains not only threatens ecological systems, but increases in precipitation could be hazardous for populations due to removal of natural flood defenses (Postel and Richter, 2003; Arthington, 2012).

E.0.5 Russia/ Eastern Europe

Russia and Eastern Europe generally show little to no significance in quantile-specific EOF1 and EOF2 relationships in the analysis, with the exception of some basins in Western Russia and Siberia. Dai (2012) predicts drying over Russia and Eastern Europe under El Niño conditions in the future due to both changes in precipitation and evaporation. Other studies have shown increase in precipitation under AMO and drying under ENSO. One key sensitivity is seen in the Yenisei basin with response to EOF2 ($-0.46 \text{ mm}/^{\circ}\text{C}$ and $1.04 \text{ mm}/^{\circ}\text{C}$ in $\tau = 0.2, 0.8$ respectively) and to EOF1 ($1.05 \text{ mm}/^{\circ}\text{C}$) in $\tau = 0.2$. Human impacts in the basin are relatively low due to sparse population, but reservoir development downstream and earlier snowmelt upstream have led to flow alteration, threatening native species (Gorshkov et al., 2013; Yang et al., 2004). Changes in precipitation coincident with changes in temperature and human water use patterns may further stress this system. Highly populated basins in Western Russia such as the Volga, Ural, and Don river basins largely suffer from water quality issues due to high industrial activity, with growing reduction in quantity contributing to quality issues. The Volga serves as the primary water supply for Moscow, with demands steadily increasing. Ecologically, flow alteration in the Ural basin due to reservoirs and hydroelectric dams has threatened the native sturgeon population (Lagutov, 2008). Russia has been highly affected in the past by drought with economic, environmental, and social consequences (Lupo et al., 2014). Potential drying over Russia, particularly with a projected increases in temperature, may cause more water quantity problems to manifest.

E.0.6 South America

South American basins show the overall highest magnitude of sensitivity to EOF1 and EOF2. While studies have shown a significant influence of ENSO on precipitation on various temporal scales (Ropelewski and Halpert, 1987; Misra, 2009; Grimm and Tedeschi, 2009; Kayano and Capistrano, 2014), it has also been shown that AMO contributes to

precipitation variability in Brazil (Knight et al., 2006; Kayano et al., 2016). The Orinoco and Amazon basins are found to undergo significant decreases in $\tau = 0.2$ and 0.8 conditioned on EOF1. Population density is low in the Amazon basin as is the pressure on resources due to high recharge rates, with withdrawals largely for agriculture and drinking water uses. However, low infrastructure capacity makes populations locally vulnerable to drought and flood conditions. Deforestation coupled with changes in soil moisture content, increases in temperature, and decreases in precipitation have led to severe droughts such as in 2005 and 2010 (Lewis et al., 2011). Projected decreases in soil moisture in the future both due to evaporation and precipitation changes is likely to increase the probability of drought in the future (Dai, 2012). Conversely, the Parana and Uruguay basins both have high population densities, with the Parana providing water to the cities of Sao Paulo, Buenos Aires, and Brasilia. While groundwater resources in the basin are heavily relied upon for municipal use, agriculture, and industry, over-exploitation of resources is variable with demand exceeding recharge in some locations (Hirata et al., 2007; Richey et al., 2015). The extremes of the annual precipitation distribution have a higher magnitude response in these basins than other locations, indicating the greatest potential changes in both magnitude and variability depending on EOF1 and EOF2 conditions. However, for areas with high population density, smaller magnitude responses can have potentially more severe impacts due to challenges in water supply, demand, and infrastructure.

E.0.7 North America

Basins in North America generally show significant response to both EOF1 and EOF2. Studies have shown ENSO to have a significant impact on US west coast precipitation, with El Niño associated with wet conditions (Meehl et al., 2007; Whan and Zwiers, 2017). For example, The Colorado River basin shows positive response to EOF1 (1.43 mm/°C and 1.87 mm/°C in $\tau = 0.2$ and 0.8) and non-significant negative responses to EOF2. The Colorado basin is highly stressed due to high population density and water demand,

infrastructure development, and natural precipitation and streamflow variability, often running dry from overuse. With 1 in 10 Americans receiving drinking water from the basin, and high agricultural demands, the basin is both economically and socially important. Furthermore, human and climate-induced stress has an impact on local ecosystems, with particular vulnerability to native fish especially close to urban centers (Olden and Poff, 2005; Paukert et al., 2011). Similarly, the Sacramento basin has high population density and accompanying water demands for agriculture, municipal, and industrial uses. $\tau = 0.8$ shows an increase of 4.99 mm/°C under EOF1 suggesting a higher probability of extreme wet precipitation during strong EOF1 conditions. However, recent persistent drought in the West has led to severe water shortages due to lower than normal precipitation and high demand and over-exploitation of both surface and groundwater resources (Richey et al., 2015). Prolonged droughts and warmer waters have also further threatened the endangered Chinook Salmon runs (Yates et al., 2008). In the Southeast United States, the Alabama and Tombigee and Suwannee basins exhibit significance responses to EOF1 in $\tau = 0.2$, and EOF1 and EOF2 in $\tau = 0.8$. While these basins contain nodes of high population density, water resources are less stressed than in other regions. Surface water makes up 95% of withdrawals in Alabama, with groundwater resources generally unstressed (Harper and Turner, 2010). However, the karst nature of the High Floridian aquifer in the Suwannee basin increases the risk of groundwater-surface water contamination via mixing when rivers experience prolonged high or low flows largely influenced by precipitation (Crandall et al., 1999). Additionally, low flows in the Suwannee river basin have been shown to reduce the transport of Dissolved Organic Carbon which is critical to ecosystem processes (Mehring et al., 2013). In the Northeast, the Penobscot river basin shows a significant decrease in $\tau = 0.8$ conditioned on EOF2 (-1.00 mm/°C). The Penobscot is both ecologically and economically important to the Atlantic Salmon population, with flow alterations due to infrastructure development, precipitation, and warming impacting migration patterns,

cues, and overall ecosystem health (Bunn and Arthington, 2002; National Research Council, 2004).

A continent-scale basin assessment highlights areas of significant sensitivity as well as provides a placed-based context for major water uses, stresses, and challenges associated with each basin. A basin with lower magnitude sensitivity may experienced amplified impacts due to already existing water stresses, governance challenges, limited infrastructure capacity, population density, or ecological vulnerability. Furthermore, when precipitation changes coincide with other drivers such as land-use alteration, temperature changes, and other anthropogenic activities, existing issues can be exacerbated, or in some cases minimized. Depending on the particular challenges and water-related activities of a location, the phase and magnitude of EOF1 and EOF2 can result in a wide-range of impacts and can be used to inform decisions in many different contexts.

Table E.1: Regression Coefficients ($\tau = 0.2, 0.8$) for SST Covariates Across Selected Basins.

Continent	Basin	$\tau = 0.2$		$\tau = 0.8$		Typology	
		EOF1	EOF2	EOF1	EOF2	EOF1	EOF2
Africa	Pangani	4.11 *	2.88	6.17 *	-2.04	a	e
	Tana	2.73 *	4.63 *	4.95 *	0.91	a	b
	Niger	-0.31	3.12 *	-1.08 *	3.13 *	f	a
	Lake Chad	-1.10 *	2.14 *	-1.55 *	2.28 *	i	a
	Sassandra	-1.96	9.35 *	-1.42	9.61 *	e	a
	Volta	-1.11	3.78 *	-1.03	4.47 *	e	a
Australia/ Southeast Asia	Blackwood	-1.40 *	-1.58	-1.51	-4.67 *	h	f
	Murray	-2.44 *	-0.14	-2.98 *	-1.46	i	e
	Pahang	-7.95 *	14.58 *	-4.72	13.62 *	h	a
	Kelantan	-13.11	13.32	-12.90	12.05	e	e
	Kinabatangan	-20.10 *	2.93	-18.45 *	4.72	i	e
Asia	Ganges	-2.27	-2.08	-2.64 *	-1.42	f	e
	Indus	-0.81	-1.58	-0.04	0.15	e	e
	Don Jiang	3.50	-5.53	7.22 *	6.90	d	e
	Mekong	-2.34 *	1.33	-2.76 *	4.72 *	i	d
	Huang He	-1.42 *	-0.28	-0.44	0.32	h	e
Europe	Garonne	1.85 *	-1.01	3.92 *	-3.65	a	e
	Thames	2.29 *	3.02	-0.01	-0.33	b	e
	Rhone	1.07	-0.58	5.76 *	-3.99	d	e
	Seine	1.55	0.66	2.99 *	0.84	d	e
	Guadalquivir	-0.62	0.11	-0.23	8.77 *	e	d
	Danube	1.00 *	0.77	-1.29	1.11	b	e
Eastern Europe	Volga	0.38	0.12	-0.11	-0.48	e	e
	Ural	0.35	0.62	0.45	0.11	e	e
	Yenisei	-0.46 *	1.05 *	-0.31	1.04 *	h	a
	Don	0.32	0.15	-0.03	-0.78	e	e
South America	Orinoco	-8.16 *	-2.85	-7.69 *	4.92	i	e
	Parana	3.07 *	-1.44 *	2.80 *	1.10	a	h
	Uruguay	7.34 *	-4.35	9.57 *	0.94	a	e
	Amazonas	-3.36 *	1.12	-4.90 *	-0.73	i	e
North America	Colorado	1.43 *	-0.77	1.87 *	-1.72	a	e
	Columbia	-0.72	0.15	-0.45	-3.64 *	e	f
	Suwannee	5.73 *	0.81	6.92 *	-5.59 *	a	f
	Alabama	4.10 *	2.82	4.35 *	-7.22 *	a	f
	Penobscot	0.42	-1.00 *	-5.04	1.79	e	h

* Significant at $\alpha = 0.1$

APPENDIX F

SUPPLEMENTAL MATERIAL FOR CHAPTER 5

F.1 Selection of Quantiles to Represent Tail Responses

The conditional quantile response can be evaluated for any τ where $0 < \tau < 1$, providing flexibility for evaluating changes over the range of outcomes and thresholds in human and environmental systems. The entire precipitation probability distribution function (PDF) can be estimated using quantile regression (QR). For this study $\tau = 0.2$ and $\tau = 0.8$ are chosen to represent the annual precipitation tails. For annual precipitation data, $\tau = 0.2$ refers to the precipitation total that is less than 80% of the historical annual totals, and $\tau = 0.8$ is less than 20% of the recorded totals. To demonstrate the range of trend estimations achieved by the QR model, and how linear regression (LR) mischaracterizes the quantile response across precipitation levels, two grid locations are selected in the United States for comparison (Figure F.1). For each location, the annual precipitation data is evaluated for all $0 < \tau < 1$ at 0.1 intervals. Significance is tested using the wild bootstrap method with $n = 1000$ (see Chapter 5 methods for more details on wild bootstrap). For the location marked in blue, there is a significant mean trend. LR assumptions imply that the trend in the mean is the trend across all quantiles with the entire distribution showing a shift in location without a change in variance. The quantile coefficient estimations show that only $\tau > 0.4$ is significantly changing with the coefficients close to 0 mm/yr in the lower quantiles. Thus, LR underestimates the risk of dry conditions. Conversely, the location marked in green shows a significant positive response for most $\tau < 0.5$ and largely non-significant changes in the upper tail. LR estimates an increase in the position of all quantiles, thereby overestimating the risk of wet conditions. Analysis of these two grids help to highlight the range of sensitivities across quantiles. $\tau = 0.2$ and $\tau = 0.8$ are chosen as thresholds to represent the tails due to sample size. QR places higher weights on the

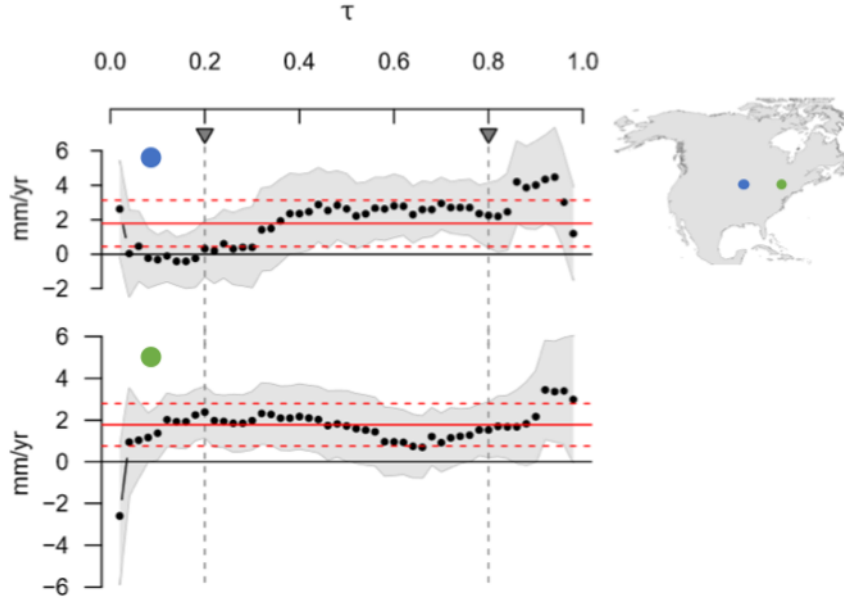


Figure F.1: Linear quantile regression coefficient estimates over the full range of quantiles (τ) for two sample locations in North America. Gray shaded areas show the 90% confidence interval (CI) with significance determined using wild bootstrap ($n = 1000$). The solid red line shows the mean trend with dashed lines showing the 90% CI. Locations of $\tau = 0.2$ and 0.8 are marked. In both examples, the mean trend over or underestimates the trend at different parts of the distribution.

points closest to the specified quantile, resulting in very high and low τ being sensitive to few data points. With a sample size of 67 years, the coefficient estimations for quantiles $\tau < 0.2$ and $\tau > 0.8$ tend to have higher errors producing unreliable estimates. Coefficient estimates at $\tau = 0.2$ and $\tau = 0.8$ are similar to estimates in more extreme quantiles, and often are even conservative estimates of changes in the tails. With a larger sample size, higher and lower quantiles could be selected due to lower estimation errors.

F.2 Assessment of Change at Specified Thresholds

For the selected grid location in the upper panel of Figure F.1, the conditional quantile regression lines and mean trend show marked asymmetric changes over time (Figures F.2). A comparison of the regression lines clearly demonstrates that the slope coefficients of $\tau = 0.2$ and 0.8 are unequal, and that variability in year to year precipitation totals has

increased over time at this location. Only $\tau = 0.5$ and 0.8 show significant changes, while $\tau = 0.2$ shows low magnitude non-significant change (0.3 mm/year). LR assumes that the precipitation PDF has constant variance and that the entire distribution undergoes a location-shift with the conditional mean. Thus, at this location LR will underestimate precipitation variability, and underestimate the risk of experiencing a high precipitation total. As noted in Figure F.1, QR can be used to evaluate changes at any threshold in the distribution and can characterize the entire range of precipitation variability over time.

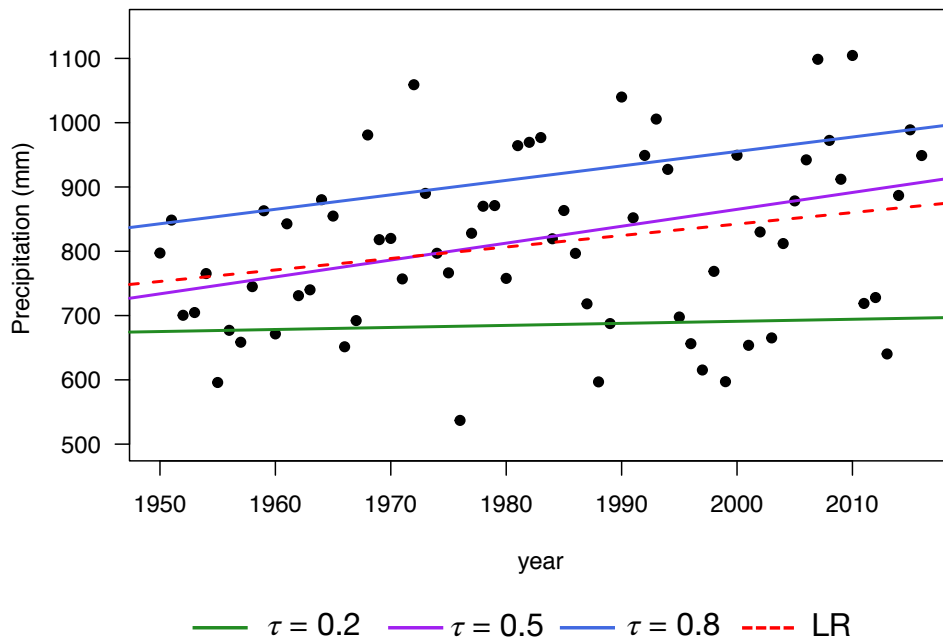


Figure F.2: LR mischaracterizes risk at thresholds in the upper and lower tails of the annual precipitation distribution. Conditional trend estimates at the blue marked location in Supplementary Figure 1. LR, $\tau = 0.5$ and 0.8 are all significant at $\alpha = 0.05$. QR can be used to estimate the trend at any threshold of the precipitation distribution, characterizing the entire range of variability.

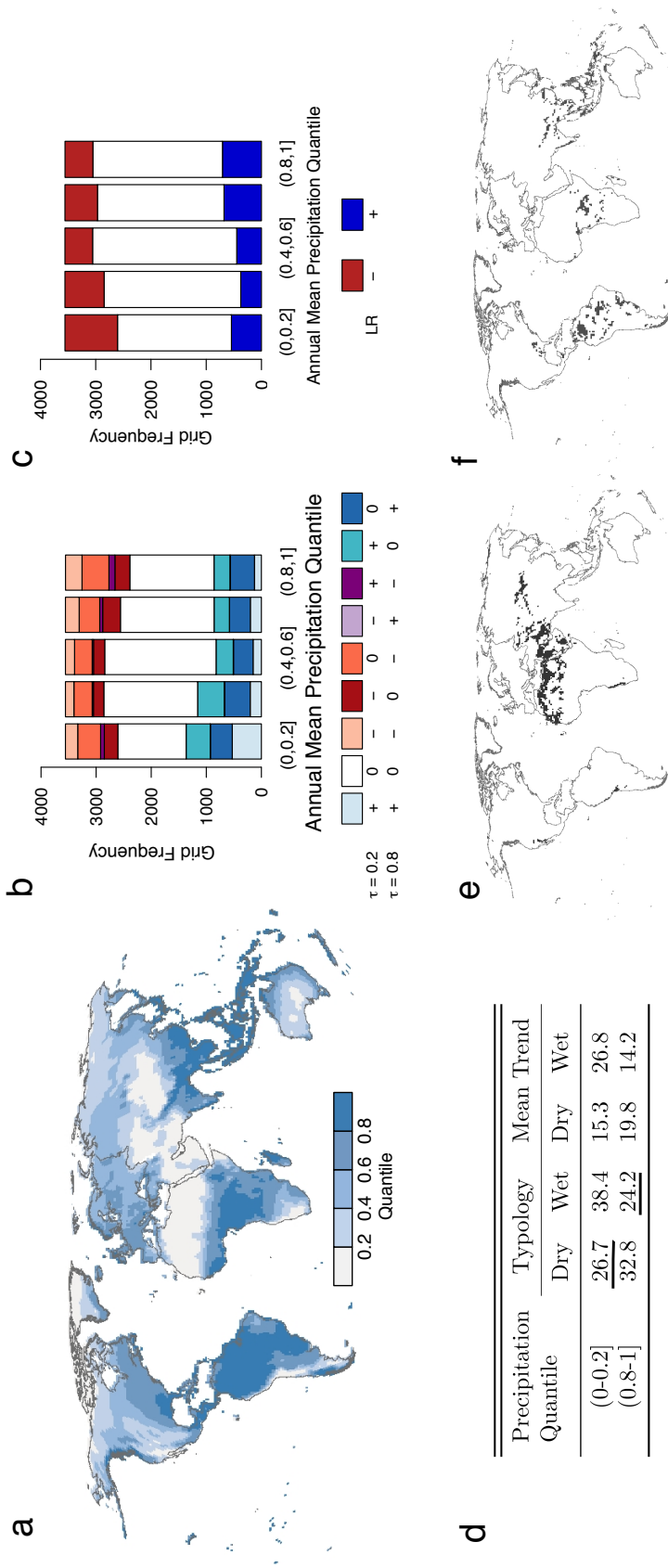


Figure F.3: Assessment of trends in annual precipitation conditioned on the long-term mean precipitation totals. a) Global pattern of mean annual precipitation, expressed as quantiles. b-c) Frequency of typologies and mean trend across quantile ranges. d) Area in the driest 20% and wettest 20% of global regions coinciding with typologies and mean trends showing increased risk of wet and dry conditions. Underlined values indicate dry areas with increased risk of dry conditions, and wet with wetter conditions. e) driest regions undergoing decreases in precipitation and f) wettest regions getting wetter. Greenland excluded from analysis.

F.3 Trend Typologies in Driest and Wettest Regions of the World

The frequency of trend typologies coinciding with the long-term annual mean precipitation totals show the nature of change for dry and wet regions of the globe (Figure F.3). Annual mean precipitation totals grids were ranked and placed in quantile bins subdividing the globe into very dry to very wet regions. The frequency of typologies falling in each bin were identified, as were the frequency of positive, negative, and non-significant mean trends. Figure S3 indicates that the driest and wettest regions of the globe are characterized by higher frequencies of significant trends than the middle 20%. In both the driest ($[0, 0.2)$) and wettest ($[0, 0.8)$) regions of the globe approximately 25% of each region is characterized by negative and positive trends in single or both tails respectively. This reflects increasing differences between wet and dry areas. However, increased probability of wet conditions in dry areas and drying in wet areas are evident as well. Comparison with LR shows that the mean trends follow a similar pattern of positive and negative trends but underestimate the affected area. As such, QR detects overlooked trends in all regions of the globe, but particularly in the wetter and drier areas where sensitivities to change may be higher.

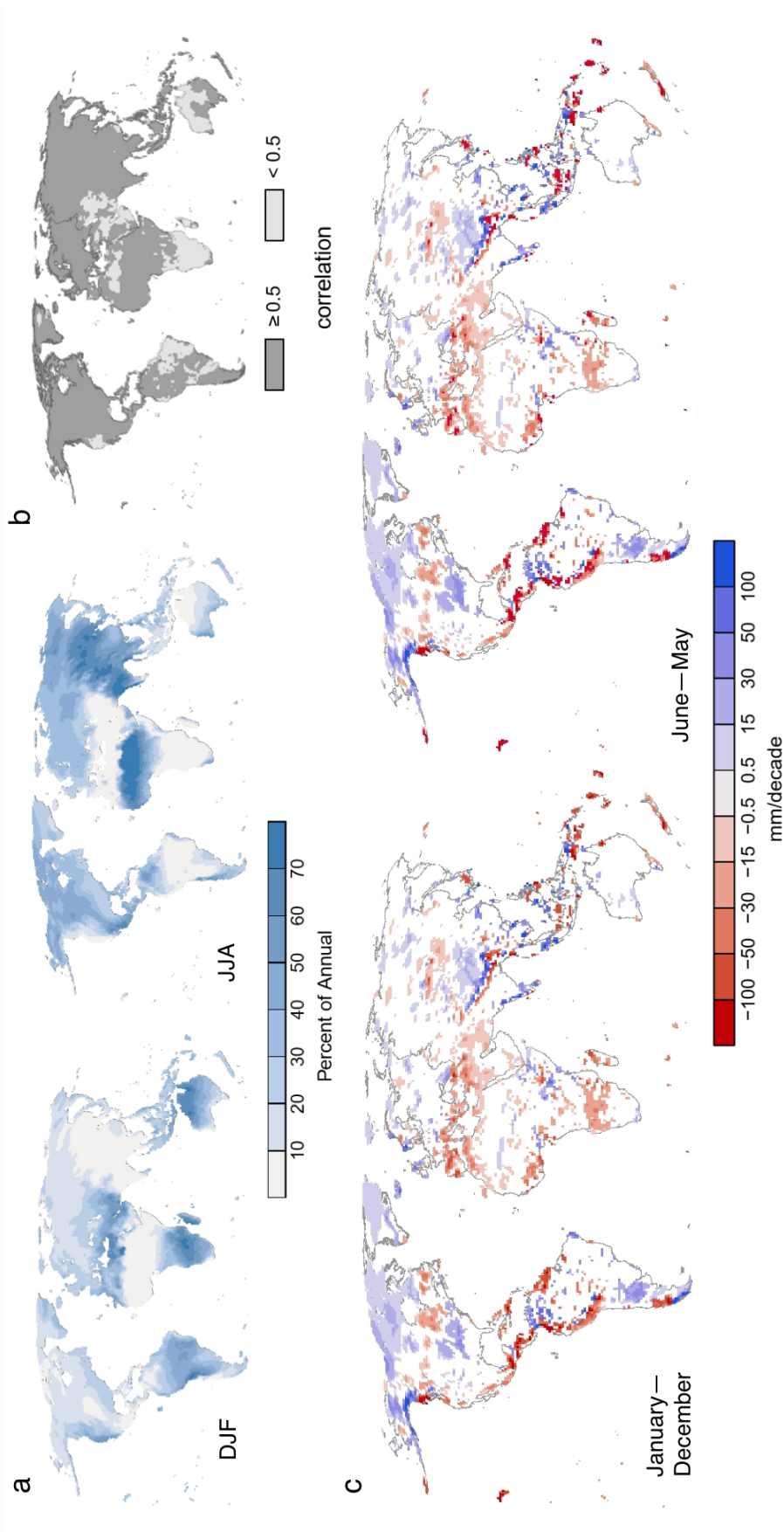


Figure F.4: Annual definition impacts annual totals. a) Average percent contribution of winter and summer seasons to annual precipitation. b) correlation of annual totals using a January–December and June–May annual definitions. For locations with high percentages of annual rainfall in DJF, the correlation is poor. c) Annual mean trend for 1950–2016 using January–December and June–May annual definitions. The correlation between regression coefficients is $r = 0.99$. Change in annual definition does not significantly impact mean trend.

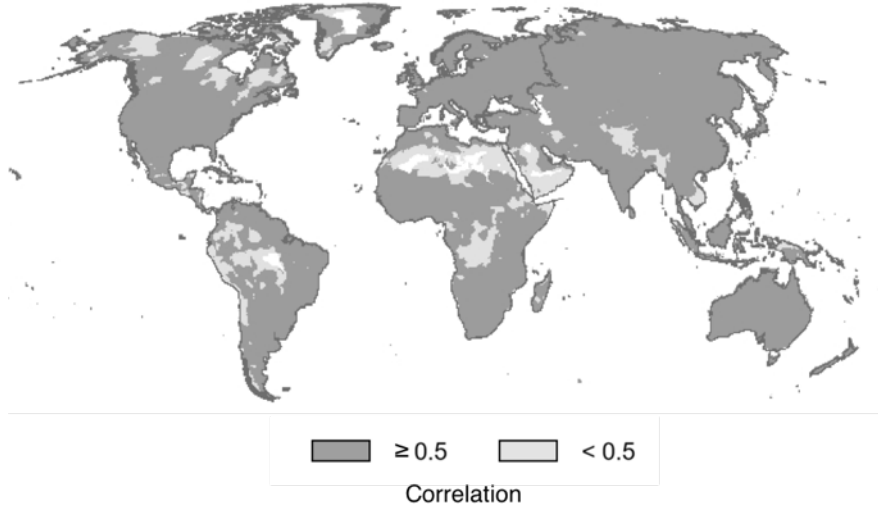


Figure F.5: Correlation coefficient of annual precipitation time-series (1950 - 2011) NOAA PREC/L and CRU TS4.01 datasets at 0.5 x 0.5 degree resolution. Correlation of mean annual precipitation between the two datasets is $r = 0.95$.

F.4 Autocorrelation of Annual Precipitation Totals

An underlying assumption of statistical methods for assessing climatic trends is that observations are independent, and the time-series is stationary. Violations of these assumptions can lead to erroneous trend significance calculations. To ensure that QR trend results are not biased due to year-to-year persistence in the precipitation data, autocorrelation (Box et al., 2015) was applied to the annual precipitation totals. Autocorrelation is defined by:

$$r(k) = \frac{\sum_i^{N-k} (Y_i - \bar{Y})(Y_{i+k} - \bar{Y})}{\sum_{i=1}^N (Y_i - \bar{Y})^2}$$

Where $r(k)$ is the autocorrelation at lag k , N is the number of observations, and $Y_1, Y_2, Y_3, \dots, Y_N$ are observations at equally spaced time intervals. We compare the autocorrelation of PREC/L at a $0.5^\circ \times 0.5^\circ$ resolution (NOAA Earth System Research Laboratory Physical Sciences Division, 2017) and CRU TS4.01 monthly precipitation (Harris et al., 2014) datasets on a June - May annual year from 1950 - 2011. Following a procedure used for other annual precipitation total time-series (Sun et al., 2015), the data

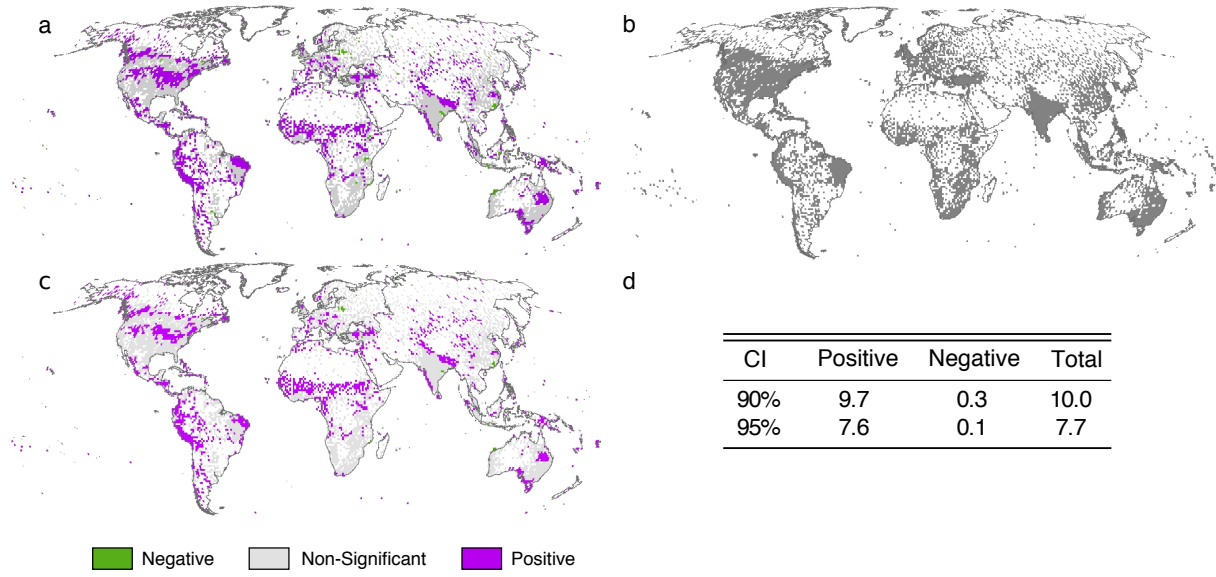


Figure F.6: Lag 1 autocorrelation of annual precipitation trends (1950-2016) a) 90% confidence interval (± 0.2). b) 95% confidence interval (± 0.244). c) Autocorrelation is only evaluated for grids with at least 1 station (27.0% of total grids) d) The percentage of land area grids (excluding Antarctica) with significant lag 1 autocorrelation at 90% and 95% confidence intervals (CI).

was first screened based on the number of gauges present in each 1 x 1 grid cell (Chen et al., 2002). Autocorrelation was only performed on grid cells with at least 1 gauge present in the 1950-2016 record (Figure F.6). The distribution of autocorrelation follows a normal distribution, with the 90% and 95% confidence intervals evaluated at $\pm 1.65/\sqrt{n}$ and $\pm 2.0/\sqrt{n}$ respectively, where n is 67 years. Results show that 7.7% of all land area grids show significant lag 1 autocorrelation at a 95% confidence interval. The impacts of episodic events on precipitation persistence are minimized by selecting a June - May annual year designation that better captures monsoonal precipitation as well as evolving ENSO conditions that often initiate and mature over the summer-fall-winter period.

Table F.1: Global Significant Precipitation Trend Patterns Across Quantiles for Positive, Negative, and Non-significant Trends in LR.

Slope LR	Trend Slopes τ :				Slope LR	Trend Slopes τ :				
	0.5	0.2	0.8	%*		0.5	0.2	0.8	%*	
+		+	+	+					59.7	
		+		+				-	8.4	
				+			+		8.0	
		+	+					+	4.9	
			+			+			3.9	
			+	+				-	3.5	
		+				+	+		2.7	
									3.0	
			-	+				+	-	2.1
										1.3
-		-	-	-					33.8	
		-	-						18.0	
		-		-					16.2	
				-					11.9	
			-						7.8	
		-							4.1	
			-	-					4.1	
									3.5	
			+	-					0.3	
		-	+	-					0.2	
	⋮	⋮	⋮					⋮		
None									66.2%	
									1.1	
									1.0	
									0.2	
									0.2	
									0.2	
									0.2	
									0.1	
									0.1	
									0.1	
								0.1		
								0.1		
								< 0		

* percentage of group total

Table F.2: Rainfed Land Types Across Regions. Percentage of regional area constituted by rainfed land types sensitive to precipitation. 21.4% of total land area excluding Antarctica and Greenland is comprised of rainfed land types.

Region	Total Area 10 ⁶ km ²	Rainfed Area 10 ⁶ km ²	Rainfed/ Total %	Rainfed Landtypes (% of Rainfed)				Regional/ Total Rainfed %
				Villages	Mosaic Villages	Residential Mosaic	Populated Cropland	
Asia	44.9	8.2	18.2	20.6	14.1	48.2	17.1	28.9
Africa	29.9	7.1	23.7	3.0	7.2	69.7	20.1	25.0
Europe	9.9	5.5	55.5	6.0	6.5	68.7	18.8	19.4
North America	22.1	3.8	17.4	1.6	5.7	57.8	34.9	13.4
South America	17.7	3.5	19.9	0.8	3.1	60.7	35.4	12.3
Oceania	8.1	0.3	3.7	0.0	3.9	50.4	45.7	1.0
Total	132.6	28.4	21.4	8.1	8.3	60.4	23.1	

BIOGRAPHY OF THE AUTHOR

Anne Marie Lausier was born in Bangor, Maine in 1990. From a young age she was curious about the world around her and gravitated towards the physical sciences. While attending Bangor High School she participated in the Maine Space Grant Consortium MERITS program, where she worked in the University of Maine Department of Chemistry in Dr. Howard Patterson's lab. It was during that time that she fell in love with research and focused her attention towards water issues. As a senior, she became the Maine state winner of the U. S. Stockholm Junior Water Prize (2009) for her work on detecting pharmaceutical and personal care products in Maine surface waters. Thanks to a human geography class at BHS, Anne soon became interested in understanding the relationships between humans and the environment and with environmental policy. In the Fall of 2009, she began her studies at The George Washington University (GW) in geography and environmental studies. During her time at GW, Anne volunteered as a docent at the Smithsonian Museum of Natural History. It was in that role that she learned the value of communicating science to the general public. Her experience at the museum has shaped her perspective on how to make connections between science and livelihoods. In 2011, Anne spent an academic year at Royal Holloway University of London where she gained a more global perspective on environmental issues. She graduated *magna cum laude* from GW in 2013.

Anne returned to Maine to pursue her masters in civil engineering at the University of Maine. In 2014, she received the National Science Foundation Graduate Research Fellowship (GRFP) to develop an approach to equitable and adaptive water management. With the support of the GRFP, She decided to pursue a PhD. While at the University of Maine, Anne served as a representative on the Graduate Student Government (GSG), followed by 2 years as the GSG Grants Officer, and graduate representative on the

University Research Council. Anne hopes to work for the U. S. government at the intersection of science and policy.

In her free time, Anne enjoys knitting, reading, collecting comic books, yoga, driving her MINI cooper on rallies with MINIs of Maine, and spending time with her sisters Katherine and Rosemary. She frequently returns to England to visit her dear friends she met on her study abroad. She also is a amateur genealogist and loves spending time researching and traveling with Katherine unearthing their family history.

Anne Marie Lausier is a candidate for the Doctor of Philosophy degree in Civil Engineering from The University of Maine in May 2019.