

PROGRESS REPORT

FOOD - ENERGY - WATER

*Innovations in Storage for Resilience
in the Columbia River Basin*

Columbia River FFW



Center for
Sustaining Agriculture
& Natural Resources

WASHINGTON STATE UNIVERSITY



STATE OF WASHINGTON
WATER RESEARCH CENTER



This Progress Report and the majority of the work described in it is supported jointly by the National Science Foundation under EAR grant #1639458 and the U.S. Department of Agriculture's National Institute of Food and Agriculture under grant #2017- 67004-26131, as well as the Washington State University Graduate School. This Progress Report also includes some articles from independent projects on related topics, which we hope and expect are of interest to our readers. Where such articles have distinct funding, the appropriate funding source is noted at the end of the article.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or the U.S. Department of Agriculture.



United States Department of Agriculture
National Institute of Food and Agriculture

FOOD - ENERGY - WATER

Innovations in Storage for Resilience in the Columbia River Basin

2019 Progress Report

Compiled and edited by:
Sonia A. Hall, Georgine G. Yorgey, Julie C. Padowski,
and Jennifer C. Adam

Design by:
Brooke R. Saari

TABLE OF CONTENTS

SECTION 1: OVERVIEW

The Food-Energy-Water (FEW) System in the Columbia River Basin: Innovations in Storage for Sustainability and Resilience

Jennifer C. Adam and the Columbia FEW Team

02

This article gives an overview to the Columbia FEW (Food-Energy-Water) project, including our goal, our working definitions of sustainability (that includes environmental, economic and social aspects) and of resilience, our focus on future changes (both global changes and autonomous adaptations) and on potential technological and institutional innovations that could address friction points between the food, energy, and water sectors. This overview provides a roadmap to how the rest of the articles in this Progress Report relate to the project as a whole.

What is a FEW System, and Why Should We Care?

Michael Goldsby

06

The connections between the food, energy and water sectors means that there are trade-offs to be considered in managing existing resources. Understanding these trade-offs and their impacts on food, energy, and water security in the Columbia River Basin starts with clearly defining and conceptualizing the integrated FEW system, which is the focus of this article.

Preparing for the Decades to Come in the Columbia River Basin: Integrating a Community Perspective

Christian D. Guzman, Julie C. Padowski, and Jennifer E. Givens

08

We describe how social science perspectives are used to help us understand how communities' resilience is a central part of the FEW system's resilience. This article describes how assessing the social implications of innovations is of central importance to whether these innovations can enhance the FEW system's sustainability and resilience.

Who Cares? Bridging Theory to Practice for Food, Energy and Water

Sonia A. Hall, Jennifer C. Adam, Georgine G. Yorgey, and Julie C. Padowski

11

The Columbia FEW project is aimed at advancing basic research while providing value for managers, practitioners, politicians and other decision-makers. We strive to answer questions inspired by the FEW-related problems faced by the people of the Columbia River Basin. This article frames how the work reported on in this Progress Report translates preliminary basic research into practical terms, and highlights the potential value of this project to the region and its decision-makers.

SECTION 2: OUR CURRENT FOOD, ENERGY, AND WATER SYSTEM: WHAT FRICTION POINTS EXIST?

How Measuring Community Assets Can Inform Sustainability and Climate Resilience

Daniel Mueller and Season Hoard

14

Measures of social, human, cultural and political capitals (which capture community traits like social bonds, the state of the workforce, ability to innovate, and political leverage) can help communities identify their strengths and weaknesses and improve sustainability and climate resilience efforts across the Columbia River Basin. This article describes a data integration framework that enables us to characterize the current status of social assets that communities have that enable them to be sustainable and resilient.

A Vulnerability Analysis for the Columbia River Basin's Food-Energy-Water System

Paris Edwards

17

Changing water resources will not have equal impact across food, energy, and water sectors. This article describes our work mapping hydrologic and socio-economic vulnerability to changes in water resources across the Columbia River Basin, a product that can help decision-makers think ahead and take action with the most sensitive subbasins in mind.

Managing for Whom? Social Well-Being and the Food-Energy-Water System of the Columbia River Basin

Michael Briscoe and Jennifer E. Givens

20

This article examines how social factors both influence and are influenced by FEW resource management. This information can be used to identify solutions that could balance existing trade-offs between the FEW sectors and increase social well-being.

Understanding Interactions Between Food Production, Water Provisioning, and Water Quality in the Yakima River Basin

Sammi Grieger and John Harrison

22

In water-stressed, intensively managed agricultural valleys, like those that exist in the Columbia River Basin, sustainably managing food production systems and aquatic ecosystems requires us to develop an understanding of the relationships between water flows and nutrient fluxes over multiple decades. This article describes our efforts to do that in the Yakima River Basin.

Improving Agricultural Nitrogen Use Efficiencies from Farm to Regional Scales: Trade-Offs among Food, Energy and Water Sectors

Mingliang Liu, Jennifer C. Adam, and Claudio O. Stöckle

26

Inefficient use of nitrogen by farmers can result in excessive fertilization costs, reactive nitrogen in water bodies, and greenhouse gas emissions to the atmosphere. Therefore, nitrogen use efficiency (NUE) should be considered when examining FEW solutions that involve crop management. This article describes our work quantifying NUE, and exploring how to use this information to assess economic and environmental aspects of the FEW system.

Stream Temperature Modeling in the Columbia River Basin

Nigel Pickering

30

Water temperature is a serious concern for Columbia River fish survival in the context of a warming climate. Dams can also influence water temperature; therefore, solutions around water storage should include an assessment of the impacts of water temperature. This article describes our efforts to provide the quantitative tools needed to perform such assessments.

Minimum Instream Flows: An Empirical Study of Instream Flow Law and Policy

Adam Wicks-Arshack, Bradley Luff and Barbara Cosens

34

Flow volume and seasonality are important variables for fish survival. Minimum instream flows exist in several states, but there are limited tools and information for knowing if these rules are being met. This is a limitation for understanding the effectiveness of policies aimed at protecting fish. This article describes a new tool for quantifying when these rules are met, which will help address this gap.

Water Storage and Economic Resilience in a Managed Hydrologic System

Moses Luri and Jonathan Yoder

36

In this article we describe a tool that examines how water storage management may be used to improve a measure of economic resilience to hydrologic shocks (mainly droughts and floods). This tool can be used to simulate how targeted innovations, particularly around storage management, affect economic resilience.

SECTION 3: HOW ARE THE FOOD, ENERGY, AND WATER SECTORS EXPECTED TO CHANGE IN THE FUTURE?

The Columbia River Forecast: What to Expect of the Columbia River's Water Supply and Demand

Sonia A. Hall, Jennifer C. Adam, Georgine G. Yorgey and Jonathan Yoder

40

Although not formally part of this project, we utilize the modeling framework and results from the Columbia River Long Term Water Supply and Demand Forecast, described in this article, to provide the context for how climate change will impact water supply, irrigation demand, municipal demand, and unmet water demand in the Columbia River Basin.

Impact of Land-Use and Land-Cover Change on the Food, Energy, and Water Sectors in the Columbia River Basin

Matthew Yourek, Keyvan Malek, Mingliang Liu, Maoyi Huang, Claudio O. Stöckle, Jan Boll and Jennifer C. Adam

43

In the Columbia FEW project we consider land-use and land-cover change, driven by large-scale climate and socio-economics, and autonomous adaptation. We are investigating its ramifications to the food, energy and water sectors and their interactions in the Columbia River Basin. This article describes how we are using spatial downscaling of global land-use and land-cover change projections and hydrologic model simulations in these investigations.

Will Washington State Supplement Some of California's Expected Losses in Vegetable Production?

Fidel Maureira, Claudio O. Stöckle, Kirti Rajagopalan and Mengqi Zhao

46

The potential migration of vegetable production into the Columbia River Basin is a specific example of land use and land cover change driven by climate change. In the Columbia FEW project we consider this as both a global change and an example of autonomous adaptation by farmers to increase their profitability. This article describes our work exploring the implications of this change for the food, energy and water sectors in the Columbia River Basin.

Are Efficient Irrigation Technologies a Winning Solution in the Yakima River Basin?

Keyvan Malek and Jennifer C. Adam

49

Efficient irrigation technologies are another example of what we consider autonomous adaptations in the Columbia FEW project. In this article we describe how improving the efficiency of irrigation systems, a current and continuing trend in the region, has implications for basin-wide agricultural water availability, energy supply and demand, and the ecology of the Yakima River system.

Adaptation to Climate Change in Agriculture: What Are the Trade-Offs?

Kirti Rajagopalan, Keyvan Malek, Jennifer C. Adam, Claudio O. Stöckle, Mingliang Liu and Michael P. Brady

52

Adaptation to climate change in the agricultural sector can lead to synergies or trade-offs across the food, energy, and water sectors. In this article we explore these synergies and trade-offs when different combinations of adaptation strategies are adopted across a watershed. We hope to identify win-win-win strategies that can alleviate friction points between sectors.

SECTION 4: KEY INNOVATIONS THAT COULD RESOLVE FRICTION POINTS BETWEEN FOOD, ENERGY AND WATER NOW AND IN THE FUTURE

Greenhouse Production of Vegetables: Implications for the Regional Food-Energy-Water System

Fidel Maureira, Claudio O. Stöckle and Kirti Rajagopalan

56

Greenhouse agricultural production (a food-centered technological innovation) is a rapidly growing industry that large retailers are showing significant interest in. This article describes our efforts to explore the implications of large-scale adoption of this technology for the FEW system in Washington State, given its potential for higher yields, and different water and energy requirements as compared to traditional production methods.

EAGERS: The Tool Behind the Energy Optimizations

Ashley Mills and Dustin McLarty

58

The ever-changing energy sector continues to see increases in the demand for power and a transition towards renewables. This article describes a new method we developed to optimize existing and new power infrastructure under various future climate and demand scenarios while considering the constraints of the diverse energy sources. This framework, coupled with the food-water models developed by the Columbia FEW team, will be used to explore energy-centered innovations in terms of their ability to alleviate FEW friction points.

How Can Long-Term Water Storage Management Mitigate Problems in an Era of Resource Deficits?

Mengqi Zhao and Jan Boll

61

Managed aquifer recharge (MAR) is an approach to store water that increases water managers' flexibility in response to temporal variations in water supply and demand. Thus, MAR is a water-centered innovation that focuses on the coordinated management of water storage. This article describes a system dynamics model we developed and verified in the Yakima River Basin, that allows users to explore recharge management strategies and evaluate the innovation in terms of its ability to alleviate FEW friction points.

Technology for Trade: A Related Project on Food and Water Innovations in the Columbia River Basin

Georgine G. Yorgey, Jonathan Yoder, Kirti Rajagopalan, Sonia A. Hall, Jennifer C. Adam and Richael Young

64

This article describes the Technology for Trade project that, although not formally tied to the Columbia FEW project, is investigating three technological innovations (seasonal forecasting, consumptive use monitoring, and computer-aided "smart" water markets) and the rules that govern them, given their potential for increasing the flexibility of water allocation in the Columbia River Basin. As a collaboration between the two teams, we will simulate the impacts some of these innovations have on the FEW system in key tributaries of the Columbia River.

The Columbia River Treaty Between the United States and Canada

Barbara Cosens

66

*Ongoing discussions around renegotiating the Columbia River Treaty could be an important driver of change in certain aspects of the Columbia River Basin's FEW system. This article, adapted from an article published in *The Advocate* (2017), provides an overview of those discussions, as context for other articles in this Progress Report.*

Potential Impacts of Climate Change and the Columbia River Treaty Renegotiation on the Food-Energy-Water System

Begum Rabeya Rushi, Jennifer C. Adam, Muhammad Barik, Se-Yeun Lee, Kirti Rajagopalan, Michael Barber, Michael P. Brady, Jan Boll and Barbara Cosens

68

Given that water supply for food production is not discussed as a primary goal of modernization of the Columbia River Treaty, studies to examine impacts of the Treaty on food production are minimal. This article describes our efforts to fill this gap by simulating the combined impacts of climate change and potential Treaty changes on unmet irrigation demand along the Columbia River mainstem.

SECTION 5: TYING THE PIECES TOGETHER

Conceptual Mapping: How We Visualize the Columbia River Basin, a Large-Scale, Complex, Food-Energy-Water System

Julie C. Padowski, Jan Boll, and Sasha Richey

72

Conceptual mapping is one way to organize the complexity of a FEW system, allowing users to visualize the entirety of the associated system components and interconnections. This article describes how conceptual mapping of the FEW system is helping fill the gap between our theoretical work and our computational modeling, and is informing modeling efforts, data collection, and scenario development.

Understanding How to Assess Resilience in Human-Natural Systems

Julie C. Padowski and Stephanie Hampton

76

Achieving resilience in practice requires a common goal and understanding by managers, scientists, and community members about how their system changes over time. This includes discussing what causes these changes, and where and how new innovations or practices can be implemented to alter the trajectory of the system for a better future. This article describes our work with a resilience expert to understand how to measure resilience in the FEW system of the Columbia River Basin.

An Integrated Tool to Assess the Sustainability and Resilience of a Food-Energy-Water System

Sasha Richey, Julie C. Padowski, Dustin McLarty, Fabio V. Scarpore, Jennifer E. Givens, Kirti Rajagopalan, Sonia A. Hall, Georgine G. Yorgey, Michael Briscoe and Jennifer C. Adam

79

This article describes the STAR Calculator, which we are developing to quantitatively compare the level of sustainability and resilience of a FEW system under different conditions. It will allow us to evaluate how different technological and institutional innovations—advanced greenhouses, energy demand response, managed aquifer recharge, water markets—would affect the sustainability and resilience of the Columbia River Basin.

Looking Forward: Incorporating Feedback into the Columbia Food-Energy-Water Project

Georgine G. Yorgey, Sonia A. Hall, Jennifer C. Adam, Julie C. Padowski, Jennifer E. Givens, Michael Briscoe, Sasha Richey, and Fabio Scarpore

83

This article describes the team's collaboration with external project advisors in September 2019. This work built on previous conversations with a variety of advisors, and delved particularly into three integrating topics: 1) Key scenarios for focusing the integrated modeling work of the Columbia FEW project; 2) the STAR Calculator, our integrated tool to assess the sustainability and resilience of the Columbia River Basin food-energy-water system; and 3) perspectives on resilience, and how the concept is applied in academic and non-academic contexts.

SECTION 6: COLUMBIA RIVER FEW TEAM & AUTHORS

About the Authors

88

This 2019 Progress Report is composed of 27 articles, contributed by 38 authors. This section highlights each author and describes their positions and affiliations to Columbia FEW partner institutions.

1: Overview

The Food-Energy-Water (FEW) System in the Columbia River Basin: Innovations in Storage for Sustainability and Resilience

Jennifer C. Adam and the Columbia FEW Team

Project Overview

Natural resource management in the Columbia River Basin hinges on understanding the complex and interdependent relationships between food, energy and water (FEW). In this Basin (Figure 1), these issues revolve around the competition for limited surface water resources to sustain irrigated agriculture, hydropower generation, and instream flow requirements for endangered fish populations. Our team seeks to develop a framework for achieving maximum co-benefits between FEW sectors to foster sustainability and resilience to future change in the Columbia River Basin. Using conceptual and biophysical regional models, we are evaluating innovations in technology and institutions across multiple spatiotemporal scales, and helping develop—with stakeholder input—food, energy, and water storage management strategies that could reduce current and future competition (or friction points) between FEW sectors.

Why Study the Columbia River Basin?

The Columbia River Basin is one of the most highly managed, large river systems in the U.S., producing more hydroelectricity than any other river basin in the country. It caters to a diversity of water users with growing demands for food, energy, and water. However, this Basin is also storage-limited, with enough reservoir capacity to store only half of the river's mean annual discharge. Declines in snowpack are also reducing natural storage, making this system particularly sensitive to warming. As a result, increased tensions between water users, especially in the dry, hot summer months, can emerge when water availability is limited.

Project Goal

Our goal is to identify and examine effective strategies to co-balance benefits among the food, energy and water sectors, and increase sustainability and resilience (Box 1) across the integrated FEW system.

Box 1: Working Definitions for Sustainability and Resilience of a Food-Energy-Water (FEW) System

FEW Sustainability: *A FEW system is sustainable only if it maintains and enhances environmental health, economic viability, and social equity within the integrated FEW system, for current and future generations.*

FEW Resilience: *Resilience is a system property that describes the tendency of a FEW system to maintain structure and functions following perturbation.*

Our Central Hypothesis

We hypothesized that coordinated management of storage systems across the food, energy and water sectors could increase the sustainability and resilience of the integrated FEW system. Coordination increases *effective* storage within the overall system and enhances its capacity to buffer disturbances at multiple spatial and temporal scales.

Our Approach

We are developing, evaluating, and iteratively applying a framework spanning the continuum from theory (Aim 1) to practice (Aim 4) to understand FEW interconnections, and to quantify the change affected by innovations across the FEW sectors.

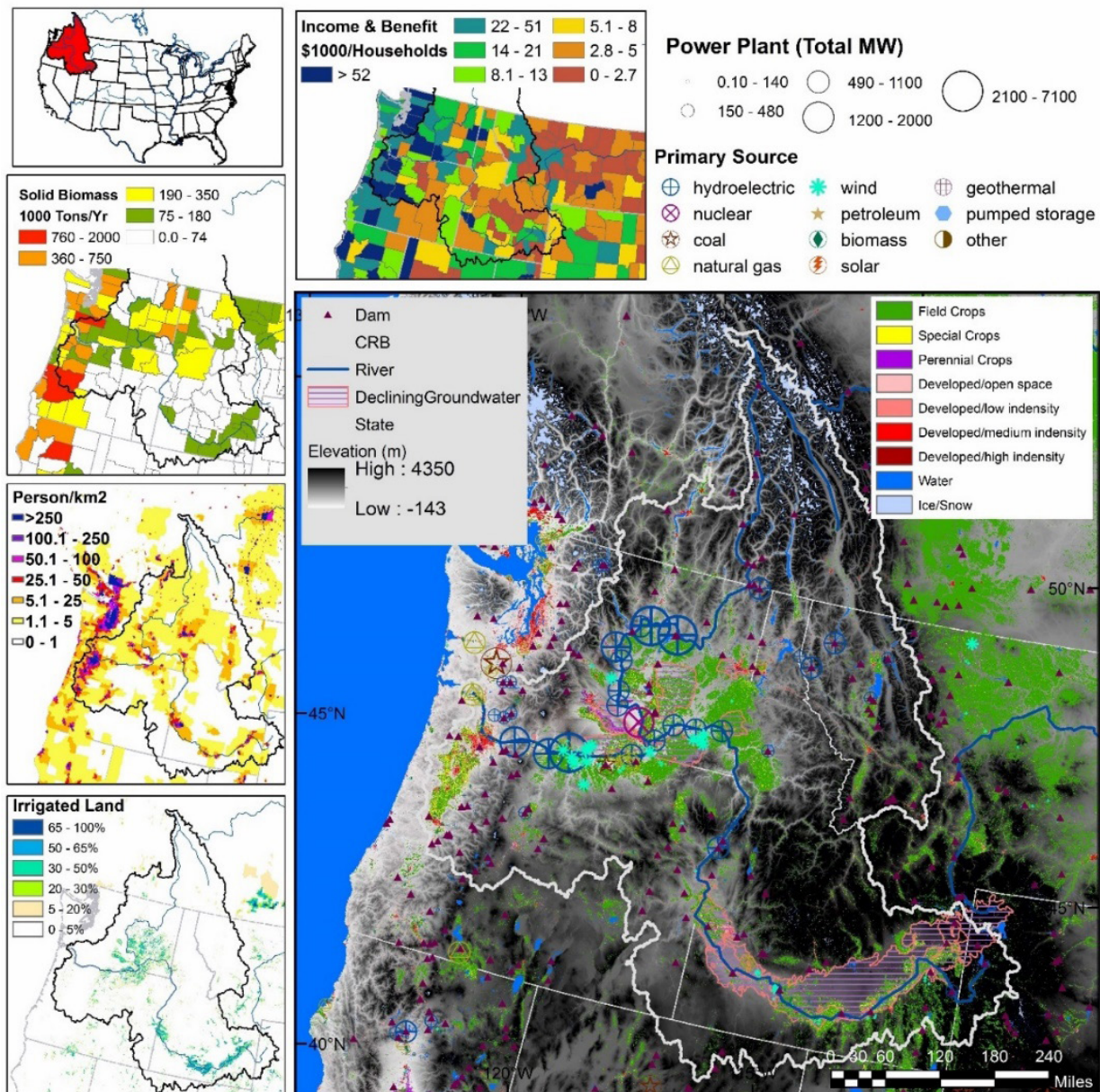


Figure 1. The distribution of food, energy, and water sectors across the Columbia River Basin. Data sources: crop distribution (Friedl et al. 2002; USDA CDL 2014); power plant distribution and generation capacity (US EIA 2016); groundwater depletion boundaries (Hortness and Vidmar 2005; Konikow 2013; USGS 2003); DEM (HydroSHEDS 15-sec DEM data; Lehner and Doll 2004); dam distribution (Lehner et al. 2011); irrigated area (Ozdogan and Gutman 2008; Siebert 2007; Siebert et al. 2005); population density (GPWv3; CIESIN-CIAT 2005); solid biomass (includes crop, forest, primary and secondary mill, and urban wood residues) (Milbrandt 2005); total income and benefit from each household in 2010 (USCB 2011).

The innovations we are assessing include technological changes, as well as innovative institutional practices or technologies focused on increasing system-wide sustainability and resilience to global change (Figure 2). Our specific aims are to:

- **Aim 1 – Problem Definition:** Develop a theoretical foundation characterizing our region’s FEW system that is generalizable to national and global scales.
- **Aim 2 – Quantification:** Integrate state-of-the-science computational models to capture FEW system interactions.
- **Aim 3 – Innovations:** Evaluate technological and institutional innovations to increase sustainability and resilience of the FEW system using the Aim 2 modeling platforms.
- **Aim 4 – Impact:** Engage scientists and other FEW experts in the region to develop new strategies to increase FEW system resilience and remove barriers to the adoption of those strategies.

Scenarios of Future Change

To achieve the aims described above, we are exploring a set of scenarios that will be run through the modeling framework and our STAR (SusTainability And Resilience) Calculator (see Richey et al.'s article). We start by considering the *status quo*: what is the situation today regarding competition for resources—friction points—between the FEW sectors? We then explore external and internal pressures or disturbances, characterizing how the FEW system may change moving into the future (Box 2). Finally, we are overlaying innovations that target existing and expected friction points, potentially benefitting the FEW system as a whole (Figure 2).

What This Progress Report Provides

We are completing the third year of an anticipated five-year project. The primary purpose of this 2019 Progress Report is to share developing insights and progress to date with regional stakeholders, including the Columbia FEW Advisory Group. Through this we hope to receive input from those knowledgeable about food, energy, and water concerns in the Columbia River Basin, to inform the remainder of our work under this project and future efforts.

We have organized the articles describing our team's progress so far into five sections. The first section provides some of the theoretical underpinnings of a FEW system, including how such a system is defined, and why the research we have undertaken is relevant. The second section contains articles that look to establish a baseline for the current FEW system in the Columbia River Basin, including identifying existing friction points. This is followed by a set of articles in the third section that quantify how different aspects of the FEW system are expected to change in the future, both in response to global change and autonomous adaptation (Box 2). The fourth section focuses specifically on the potential solutions to existing and future friction points, including examples of coordinated storage, and both technological and institutional innovations (Figure 2). We also include articles describing independent but closely related projects that are part of our collective work to better understand the issues and trade-offs surrounding the FEW system. Finally, the fifth section includes articles that discuss our team's efforts to integrate the research and results described in preceding sections to address and assess the interconnections, synergies and trade-offs between the food, energy and water sectors, and across social, ecological and economic dimensions of sustainability and resilience.

Box 2: Types of Change the Food-Energy-Water (FEW) System May Experience in the Future That Were Considered

1. Global Changes

Climate change; increases in carbon dioxide; land use and land cover (LULC) change; changes in population, industry, and FEW demands (within-basin and trade outside of the basin).

2. Example Autonomous Changes

Food: irrigation technology/management; planting date; crop variety/mix; double cropping; fallowing.

Energy: increase in non-hydro renewable energy; energy dispatch optimization.

Water: dam operations; instream flow rules; water rights expansion; tribal adjudication.

Managed aquifer recharge	Pumped hydropower	Floodplain storage	Changes in coordinated storage management
Exempt well overhaul	Water markets/ water trading	Consumptive use-based water law	Primarily institutional innovations
Smart metering/ demand shaping	Improved adjudication	International Policy	
Grid-scale energy storage	Non-hydro renewable energy	Wasted resource capture/reuse	Primarily technological innovations
New crop varieties	Precision agriculture	Greenhouses/LEDs for sunlight	

Figure 2. Potential innovations identified by our team and our Advisory Group. Orange denotes changes in coordinated storage management. The two tones of green denote innovations, including institutional (light green) and technological (dark green) innovations.

For additional information on the Columbia FEW project, please visit:

<https://s3.wp.wsu.edu/uploads/sites/1428/2018/01/ColumbiaFEW-full-article.pdf>

<https://fewstorage.wsu.edu/>

References

- Center for International Earth Science Information Network - CIESIN - Columbia University, and Centro Internacional de Agricultura Tropical - CIAT, 2005. Gridded Population of the World, Version 3 (GPWv3): Population Density Grid.
- Friedl, M., McIver, D., Hodges, J., Zhang, X., Muchoney, D., Strahler, A., Woodcock, C., Gopal, S., Schneider, A., Cooper, A., Baccini, A., Gao, F., Schaaf, C., 2002. Global land cover mapping from MODIS: algorithms and early results. *REMOTE Sens. Environ.* 83, 287–302. doi:10.1016/S0034-4257(02)00078-0
- Hortness, J.E., Vidmar, P., 2005. Surface-Water/Ground-Water Interaction along Reaches of the Snake River and Henrys Fork, Idaho (No. Scientific Investigations Report 2004 – 5115). U.S. Geological Survey, Reston, Virginia.
- Konikow, L.F., 2013. Groundwater depletion in the United States (1900–2008) (No. U.S. Geological Survey Scientific Investigations Report 2013–5079).
- Lehner, B., Doll, P., 2004. Development and validation of a global database of lakes, reservoirs and wetlands. *J. Hydrol.* 296, 1–22. doi:10.1016/j.jhydrol.2004.03.028
- Lehner, B., Liermann, C.R., Revenga, C., Vorosmarty, C.J., Fekete, B., Crouzet, P., Doll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J.C., Rodel, R., Sindorf, N., Wisser, D., 2011. Global Reservoir and Dam Database, Version 1 (GRanDv1): Dams, Revision 01. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY.
- Milbrandt, A., 2005. A Geographic Perspective on the Current Biomass Resource Availability in the United States (No. NREL/TP-560-39181). National Renewable Energy Laboratory, Golden CO.
- Ozdogan, M., Gutman, G., 2008. A new methodology to map irrigated areas using multi-temporal MODIS and ancillary data: An application example in the continental US. *REMOTE Sens. Environ.* 112, 3520–3537. doi:10.1016/j.rse.2008.04.010
- Siebert, S., 2007. Global map of irrigation areas version 4.0.1. FAO, Rome, Italy.
- Siebert, S., Doll, P., Hoogeveen, J., Faures, J., Frenken, K., Feick, S., 2005. Development and validation of the global map of irrigation areas. *Hydrol. EARTH Syst. Sci.* 9, 535–547.
- U.S. Census Bureau, 2011. TIGER/Line Shapefiles [machine-readable data files].
- USDA National Agricultural Statistics Service Cropland Data Layer, 2014. Published crop-specific data layer.
- U.S. Energy Information Administration (EIA), 2016. U.S. Energy Mapping System [Internet].
- U.S. Geological Survey, 2003. Principal Aquifers of the 48 Conterminous United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands (No. U.S. Geological Survey). Madison, WI, USA.

What is a FEW System, and Why Should We Care?

Michael Goldsby

THE CONNECTIONS BETWEEN THE FOOD, ENERGY AND WATER SECTORS MEANS THAT THERE ARE TRADE-OFFS TO BE CONSIDERED IN MANAGING EXISTING RESOURCES. UNDERSTANDING THESE TRADE-OFFS AND THEIR IMPACTS ON FOOD, ENERGY AND WATER SECURITY IN THE COLUMBIA RIVER BASIN STARTS WITH CLEARLY DEFINING AND CONCEPTUALIZING THE INTEGRATED FOOD-ENERGY-WATER SYSTEM.

Food, energy, and water sectors are connected in important ways; what affects one sector is likely to have consequences for the others, resulting in trade-offs between the sectors. For example, increasing agricultural water use may have impacts on the amount of water available for power generation or municipal usage. Understanding those connections and the attendant trade-offs will help society more efficiently ensure food, energy, and water security. As a result, there has been a push to consider food, energy, and water not as three separate yet interconnected systems, but rather as a single integrated Food-Energy-Water (FEW) system. This integrated approach might help scientists, managers and broader society understand when management decisions could become lose-lose-lose strategies across all three sectors (Figure 1).

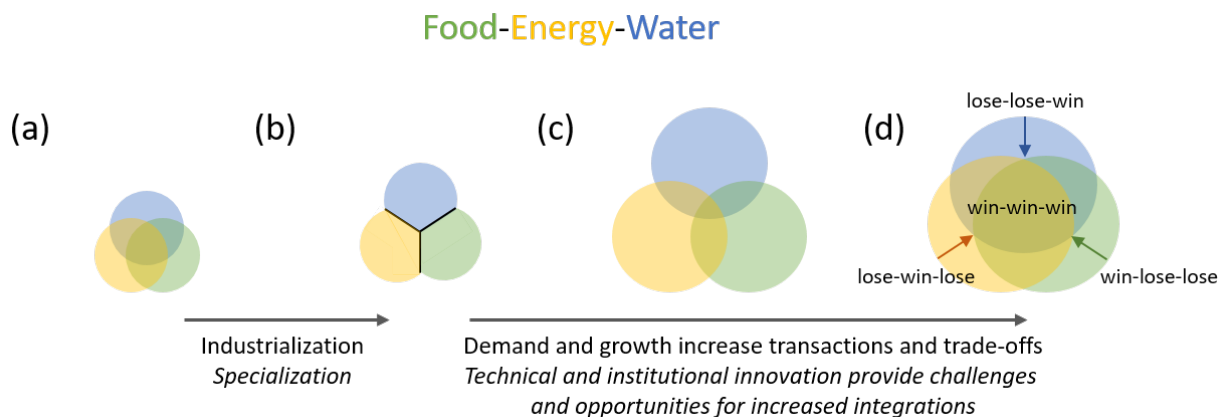


Figure 1. The interconnections between the food, energy and water sectors have evolved over time. The current integrated approach is meant to help scientists, managers and broader society identify win-win-win strategies across all three sectors. Figure developed based on a presentation by Paul Roberts, journalist.

Defining a FEW system is not as easy as coming up with a catchy acronym. A good working definition must be able to:

- 1) distinguish FEW systems from non-FEW systems,
- 2) be useful to managers and scientists working in each sector, and
- 3) be adaptable enough to allow resource managers to make good management decisions within their own jurisdictions.

If one simply defines a FEW system as any “system” that manages food, energy, and water, then nearly every living thing counts. Bears, ducks, and even mosquitoes manage food, energy, and water resources, but they are not what we would study as FEW systems. Moreover, there is no human endeavor that is not affected by concerns about food, energy, and water security. As such, there is a temptation when conceptualizing the FEW system to have it include everything. This presents a problem, because a model of a FEW system that includes everything is neither possible nor practical. So, an adequate definition of FEW systems must be more specific, and must focus on relevant predictors and leverage points, while excluding factors that are not that relevant to the core system (see Padowski et al.’s conceptual mapping article).

Conceptualizing a FEW system faces another difficulty: the study and management of FEW resources tend to be highly specialized. Hydrologists see FEW difficulties as water issues, agronomists think of FEW in terms of crop yields and markets, and energy specialists couch the issues around energy production. That by itself is not necessarily bad;

however, for FEW research to be effective, it must be accessible to scientists, managers, and producers from all three sectors. In other words, the FEW system must be conceptualized generally enough to provide actionable information to all three sectors, but specialized enough to be of use to each. Our team has the goal of providing a way to measure the integrated “health” of a FEW system (see Richey et al.’s article), in a way that can easily be translated to terms that managers in each sector can understand.

Other issues include scale and boundaries. With regard to scale, some scientists and scholars conceive of the FEW system as a global system encapsulating the food, energy and water sectors throughout the entire world. This conceptualization is too large to be of use to most resource managers, as it is unlikely that political situations will allow for the global management of this global FEW system. The study of a FEW system needs to be applicable to particular resource managers’ area of authority and concern.

With regard to defining the boundaries of a FEW system, some have suggested watersheds, food distribution networks or power grids. The problem is that those boundaries are rarely co-extensive, so choosing one over the others is arbitrary at best. Moreover, resource managers and producers rarely have influence over an entire energy grid, food distribution network, or watershed. If the goal is to provide decision-relevant information to resource managers in an effort to improve FEW security, efforts to define a FEW system in those ways will fail.

In order to avoid the pitfalls mentioned above, we look for certain traits that make up a FEW system. According to our understanding, a FEW system must have three traits:

- 1) There must be specialization in the production and management of the resources. Food producers produce food, water managers manage water, and the energy sector is likewise focused on energy;
- 2) Resources in one FEW sector may be traded off with resources in another sector; and
- 3) Scarcity in one sector has the potential to propagate throughout all three sectors.

This definition is somewhat permissive, but not so permissive as to count bears and ducks. Additionally, this conceptualization allows for nested and overlapping FEW systems. The Yakima River region is a FEW system as it has all three traits mentioned above, and it is a FEW system fully contained within the Columbia River Basin FEW system, which in turn is part of the North American FEW system, which itself is part of the global FEW system (Figure 2). The strength of this definition is that it allows serious research into the interactions of FEW systems, while still allowing for meaningful action on the part of resource managers.



Figure 2. Nested food-energy-water (FEW) systems in the Pacific Northwest.

Preparing for the Decades to Come in the Columbia River Basin: Integrating a Community Perspective

Christian D. Guzman, Julie C. Padowski and Jennifer E. Givens

THE SOIL, WATER, ECOSYSTEM, AND ECONOMIC RESOURCES IN THE COLUMBIA RIVER BASIN ARE MANAGED BY LEADERS AND INSTITUTIONAL ORGANIZATIONS REPRESENTING COMMUNITIES OF THIS REGION. INNOVATIONS AIMED AT SOLVING THE PRACTICAL ISSUES ACROSS COMMUNITIES HELP TO PRODUCE MANAGEMENT STRATEGIES THAT ENABLE ADAPTATION TO NEW, UNCERTAIN ENVIRONMENTAL CONDITIONS AND ENCOURAGES COOPERATION IN DEFINING FUTURE GOALS AND LIVELIHOODS. SOCIAL SCIENCE PERSPECTIVES HELP US UNDERSTAND HOW COMMUNITIES' RESILIENCE IS A CENTRAL PART OF THE FOOD-ENERGY-WATER SYSTEM'S RESILIENCE.

The Great Depression of the 1930s demonstrated how recessions can deeply, persistently, and unevenly disrupt society through interaction with environmental stresses (water scarcity and soil erosion). While scientific advances, stabilizing economic policies, and the return to pre-disruption environmental conditions may lead to full recovery of economic indicators, lived experiences and oral histories remind us that communities are altered in profound ways, often with long-term implications. With the loss of livelihoods, capital, and community networks comes a breach in the pre-existing social fabric that recovers in ways different than improved unemployment numbers and reconstruction rates might suggest.



Figure 1. Wheat farmer with his mules, farming technology commonly used around the time of the Great Depression. Whitman County, Washington. Photo: Library of Congress, 1941 (<https://www.loc.gov/pictures/resource/fsa.8c35303/> and <https://www.loc.gov/pictures/item/2017790210/>).

The Columbia River Basin is projected to experience technological, economic and climatic shifts over the next several decades; specifically, studies estimate between 0.2°F to 1.0°F (0.1°C to 0.6°C) rise per decade (Mote and Salathé 2010). How will these shifts translate into local impacts that alter existing social structures and dynamics in each community? What impacts has the rise in temperatures already caused locally, in your community? In your region? As political, economic and demographic trends continue to evolve, this rise in annual average temperatures, along with other changing climatic variables, has the capacity to further heighten and intensify particular socio-ecological interactions.

Similarly, economic advances and technological innovation have led to new ways of distributing goods, transferring information and investing in institutions that build up, diversify and integrate communities. In the Columbia River Basin alone, railways, telecommunications and the Clean Water Act have had drastic impacts on how communities are able to thrive and develop. These innovations were driven by legal and institutional developments, global market forces and demographic changes, and have had important structural influences on ideas and processes used to create new technologies, regulations, and incentives (Givens et al. 2018).



Figure 2. Bergevin-Williams and Old Lowden Pipeline and Diversion in Walla Walla, Washington with water rights for some farms dating back to 1870 (<http://www.wcccd.net/district-projects/bwol-pipeline-and-diversion>). Irrigators worked with the Walla Walla Conservation District and Washington Department of Fish and Wildlife to provide improved fish passage and flow to Mid-Columbia Steelhead, while aiming for a reliable irrigation water delivery system.

In the coming decades, the food, energy and water sectors will develop independently according to specific sectoral needs. But they will also develop in co-dependent (or competing) and uncertain ways. Whether these developments occur in directions that have wide-reaching, life-improving benefits or drastic negative effects is of concern not just for academics, industry leaders or politicians, but also for the communities that plan out their futures among relatives, neighbors, and school districts. Looking forward and anticipating innovations can help water managers, farmers, public utilities and other decision-makers in these communities prepare for or take advantage of new environmental conditions. Innovations are exciting, but may lead to labor market transformations or other disruptive effects. Greenhouses for instance, have the capacity to provide new compact spaces for diversification of agricultural production (see Maureira et al.'s greenhouses article). However, the new labor skills needed might shift the composition of nearby towns. How social systems drive innovations and how they are later impacted by these same patterns is currently of interest to many social scientists, as we seek to understand the underlying dynamics at hand (see Briscoe and Givens' article).

Interdisciplinary studies help to incorporate how stakeholders perceive the food, energy and water sectors, complementing previously studied system biophysical components. Our team currently works towards this in the Columbia River Basin's food-energy-water (FEW) system by asking: Where amongst the intersections of FEW sectors does friction (competition and conflict) occur? How are these sectors influenced by the next generation of consumers and producers (e.g, in 2050 or 2100)? And how will that affect those friction points? What key innovations resolve future friction points between the FEW sectors? For instance, water rights and sharing must comply with supplying irrigation needs, ecological flow and energy demands, but also function within social structures that often enhance cooperation rather than competition (Figure 2; Givens et al. 2018).

This broad collaboration of extension researchers, university scientists, and stakeholders convened to explore innovations that can be developed with these questions in mind, using both complex, mechanistic models and simpler system dynamics models to test out scenarios of implementation under current and future conditions. At the heart of this innovation exploration is storage of the resources the Columbia River Basin social system needs the most. Ultimately, of central importance is whether these innovations enhance the resilience and sustainability of the Columbia River Basin as an environmental, economic, and social system. We aim to work towards the discovery of bold innovations driven by stakeholder insight in order to empower communities who are already at work planning their futures in these coming decades.

References

- Givens, J.E., Padowski, J., Guzman, C.D., Malek, K., Witinok-Huber, R., Cosens, B., Briscoe, M., Boll, J. and Adam, J., 2018. Incorporating Social System Dynamics in the Columbia River Basin: Food-Energy-Water Resilience and Sustainability Modeling in the Yakima River Basin. *Front. Environ. Sci.*, 6: 104.
- Cosens, B., Fremier, A., 2018. Social-ecological resilience in the Columbia River Basin: the role of law and governance. In *Practical Panarchy for Adaptive Water Governance* (eds) B. Cosens and L. Gunderson, pp. 47-64, Springer, Cham.
- Mote, P.W., Salathé, E.P., 2010. Future climate in the Pacific Northwest. *Climatic Change*. 102: 29-50.
- Yoder, J., Adam, J., Brady, M., Cook, J., Katz, S., Johnston, S., Malek, K., McMillan, J., Yang, Q., 2017. Benefit-Cost Analysis of Integrated Water Resource Management: Accounting for Interdependence in the Yakima Basin Integrated Plan. *J. Am. Water Resour. Assoc.* 53: 456–477.

Who Cares? Bridging Theory to Practice for Food, Energy and Water

Sonia A. Hall, Jennifer C. Adam, Georgine G. Yorgey and Julie C. Padowski

THE COLUMBIA FOOD-ENERGY-WATER (FEW) PROJECT AIMS TO ADVANCE BASIC RESEARCH WHILE PROVIDING VALUE FOR MANAGERS, PRACTITIONERS, POLITICIANS AND OTHER DECISION-MAKERS. WE STRIVE TO ANSWER QUESTIONS INSPIRED BY THE FEW-RELATED PROBLEMS FACED BY THE PEOPLE OF THE BASIN. THE ARTICLES IN THIS PROGRESS REPORT TRANSLATE PRELIMINARY BASIC RESEARCH INTO PRACTICAL TERMS AND HIGHLIGHT THE POTENTIAL VALUE OF THIS PROJECT TO THE REGION AND ITS DECISION-MAKERS.

Our project focuses on the Columbia River Basin's interconnected food-energy-water (FEW) system, spanning the continuum from theory to practice. The funders, the National Science Foundation and the United States Department of Agriculture, consider this a "use-inspired basic research" project. That is, the research is focused on gaining understanding of how the system works, but the focus of that basic research is targeted towards tackling questions important for decision-making. The questions we address span disciplines and sectors, such that the research results and associated insights we generate may be of interest and value to a range of different audiences, from other researchers through to managers, practitioners, politicians and other decision-makers across the food, energy and water sectors in the Basin. This emphasis underlies other projects team members are involved in within this geography and topic area, and we have included articles on these independent projects as well (see Hall et al. and Yorgey et al.'s articles), as they add to our overall understanding of the Columbia River Basin FEW system.

As researchers, we have—and commonly use—a variety of communications mechanisms (e.g. conference presentations, journal publications) to share our results with the academic community. Some of the contributions this project is making are particularly suited to academia, and also provide a foundation for more applied aspects of this same project. In contrast to these academic communications approaches, this Progress Report is meant to share results and insights gathered so far with regional stakeholders. We therefore highlight some of the opportunities we see for providing a clearer understanding of the FEW system and its interconnections, friction points, expected future changes, and strategies that could enhance the system's overall sustainability and resilience. We discuss both conceptual advances (see Goldsby's article on defining a FEW system and its sustainability and resilience, and Padowski et al.'s article on conceptual mapping across the food, energy and water sectors in the Columbia River Basin) as well as more applied work, which we envision informing different decision-making processes through:

- Quantifying expected changes in the Columbia River Basin. Changes include those that are external, such as climate change (see Hall et al.'s article on the independent Columbia River water supply and demand Forecast), as well as internal to the system (see Yourek et al.'s article on land use and land cover change, Maureira et al.'s article on vegetable migration into the region, Mills and McLarty's article on optimizing energy systems under current and future conditions, and Rajagopalan et al.'s article on adaptation in the agricultural sector). We also explore how a change in one sector can interact and affect social, economic or ecological components of sustainability in other sectors (see Luri and Yoder's article on the economic value of storage capacity, Briscoe and Givens' article on social elements as drivers and outcomes of decisions, Grieger and Harrison's article on nitrogen loading in the Yakima River, and Malek and Adam's article on consequences and trade-offs of improving irrigation efficiency). These results provide useful scenarios that can inform long-term planning and decisions.
- Quantifying the effectiveness of specific technological and institutional innovations. Different models and technological tools allow us to explore futures or 'what if' scenarios before making decisions (see Maureira et al.'s article on greenhouses, Zhao and Boll's article on managed aquifer recharge, Wick-Arshack et al.'s article on minimum instream flows, and Yorgey et al.'s article on the independent Technology for Trade project), as well as the consequences those innovations may have on other sectors to the one they are implemented in (see Cosens' and Rushi et al.'s articles on the Columbia River Treaty). These results can provide insights to practitioners considering implementing such innovative technologies, or entities advocating for improved governance or rules regulating water rights, for example.
- Informing policy discussions that foster adoption of technologies or institutional innovations that show promise for addressing current and future friction points across the food, energy and water sectors, leading to overall improvements in the FEW system's sustainability and resilience (see Padowski and Hampton's article describing stakeholders' desired futures, and Richey et al.'s article on the STAR calculator and its use for comparing innovations' effects on sustainability and resilience).

These are simply examples where we see possible links between the ongoing Columbia FEW research and decisions that impact how food, energy, and water are managed in the Columbia River Basin (Figure 1). Each article mentioned here touches on the management, policy- or decision-making implications that we see, and we look forward to deepening our understanding of these links, as well as exploring additional links that we have not envisioned. Ultimately, we hope these ongoing research contributions will help enhance the sustainability and resilience of the Columbia River Basin's FEW system, and the communities it supports.



Figure 1. *The food, energy and water sectors in the Columbia River Basin are interconnected, as visualized in these photos. Research and management, therefore, should acknowledge and consider these connections.*

2: Our Current Food, Energy and Water System: What Friction Points Exist?

How Measuring Community Assets Can Inform Sustainability and Climate Resilience

Daniel Mueller and Season Hoard

MEASURES OF SOCIAL, HUMAN, CULTURAL AND POLITICAL CAPITALS, WHICH CAPTURE COMMUNITY TRAITS LIKE SOCIAL BONDS, THE STATE OF THE WORKFORCE, ABILITY TO INNOVATE AND POLITICAL LEVERAGE, CAN HELP COMMUNITIES IDENTIFY THEIR STRENGTHS AND WEAKNESSES AND IMPROVE SUSTAINABILITY AND CLIMATE RESILIENCE EFFORTS ACROSS THE COLUMBIA RIVER BASIN.

The traits of any food-energy-water system that contribute to the system’s sustainability and ability to recover from climate shocks are numerous, including the quantities of available food, water, financial resources, reliable and low-carbon energy sources, and the responsible management of these resources. Social traits also contribute to a system’s resilience and sustainability (defined in Adam et al.’s overview article). One way to represent these traits is through the Community Capitals Framework (CCF). The CCF suggests that seven capitals—social, human, cultural, political, natural, built, and financial—contribute to a community’s overall well-being or general state of sustainability (Figure 1; Emery and Flora 2006). High stocks of these capitals are generally thought to result in happier, healthier, more sustainable communities, and they may also be linked to community resilience in the face of extreme weather events or drastic social or economic transformations, such as those that may result from climate change.



Figure 1. Community Capitals Framework and Capital Summaries. These capitals contribute to a community’s overall well-being or general state of sustainability.

When community members pursue efforts to improve the sustainability or resilience within their food-energy-water system—through the adoption of innovations like more efficient irrigation techniques or improved resource management strategies or policies, for example—it is often easier to incorporate economic elements associated with natural, built, and financial capitals in decision-making, while the social elements associated with social, human,

cultural, and political capitals may be overlooked. This is because quantitative information on the social elements can be difficult to acquire, and the available qualitative data can be expensive and time-consuming to gather. As a result, the social elements of the Community Capitals Framework may be missing in assessments of food-energy-water systems, and this can lead to inaccurate conclusions about the state of the sustainability or resilience of these systems. After all, a community may have a strong economy, the necessary stocks of natural resources, and the infrastructure needed to carry out a sustainability or resilience project, but might lack social trust, strong community networks, political will, or public support, which can undermine the success of the sustainability project. To address this issue, a research team supported by the Federal Aviation Administration (FAA) developed the Community Assets and Attributes Model (CAAM), a quantitative model that measures the social elements of the Community Capitals Framework. We applied this model to the Pacific Northwest by using several county-level, quantitative indicators that represent social, cultural, human, and political capitals (Figure 2), and are using the results to examine food, energy, and water systems and innovation adoption in the region.

Social Capital	Human Capital	Cultural Capital	Political Capital
<ul style="list-style-type: none"> Aggregate of religious, civic, business, political, professional, labor, bowling, recreational, golf, and sports organizations divided by population per 1,000 Number of non-profit organizations excluding those with an international approach divided by population per 1,000 	<ul style="list-style-type: none"> % Live births with low birth weight % Children in poverty % Unemployed Income inequality ratio Number of reported violent crime offenses per 100,000 population 	<ul style="list-style-type: none"> Proportion of population aged 16+ employed in management, business, science, and the arts % Aged 25+ with Bachelor's degree or higher 	<ul style="list-style-type: none"> 2012 general election turnout 2014 general election turnout
Source: Rupasingha , Goetz, and Freshwater (2014)	Source: County Health Rankings (2017)	Source: US Census (2015 5-year averages)	Source: Dave Leip's Atlas of US Presidential Elections (2017)

Figure 2. Indicators included in the Community Assets and Attributes Model (CAAM), which measures the social elements of the Community Capitals Framework.

To date, this model has been used in the Pacific Northwest to assess ideal siting locations for biorefineries that produce sustainable aviation biofuel, and we have used interview data to validate the model and improve its accuracy. The current version of the CAAM can be used to help assess capital stocks within a community (see Figure 3 for an example using social capital), or it can inform how to engage with community members to develop food-energy-water projects. For example, stakeholders could use the CAAM to generally assess the stocks of their community's social, cultural, human, and political capitals and combine this information with other capital data (natural, built and financial) to understand potential community resilience to climate shocks. Where there are strong social bonds, political leverage, innovation and quality of the workforce, combined with economic resources, community members will likely find it easier to work together to recover from climate shocks and develop strategies to mitigate future catastrophes.

Social Capital in the Pacific Northwest

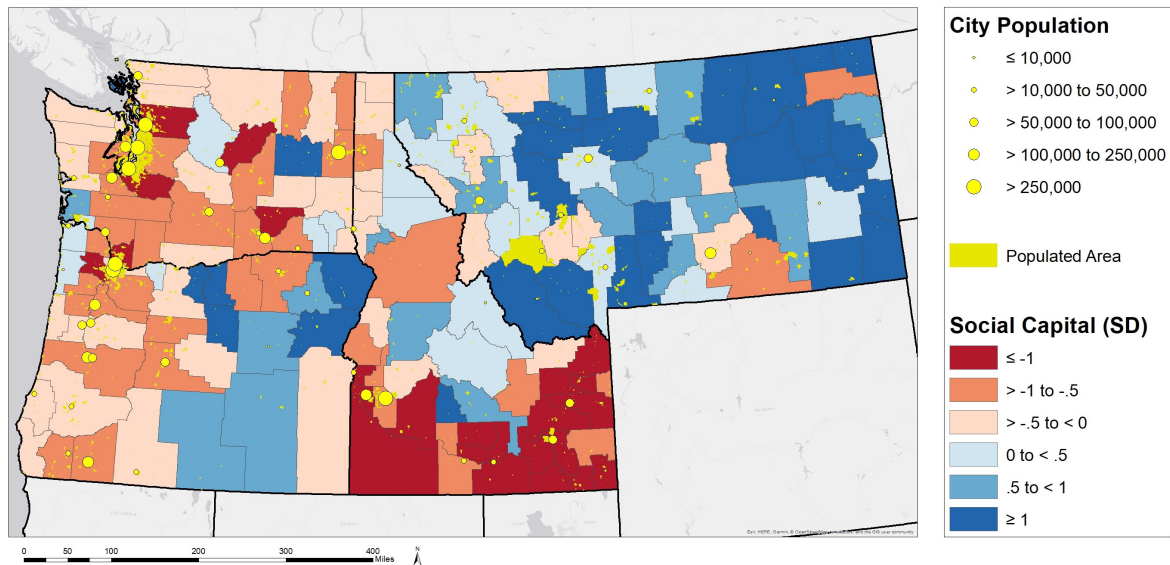


Figure 3. Social capital in the Pacific Northwest, quantified using county-level data on a range of indicators (see list in Figure 2).

Additionally, in the case of a biorefinery or other sustainability project, the social and political capital data provided by the CAAM can inform how project leaders approach and interact with community members to build trust and ensure community engagement in the decision-making process. For example, in a community where the CAAM indicates weaker social bonds or high levels of internal mistrust, project leaders would need to expend more effort to reach out to community members. The cultural and human capitals data can help assess whether or not the community has an adequate workforce to complete and maintain the project.

The CAAM therefore serves as an effective tool for stakeholders and community decision-makers, granting them quick and efficient access to social data that can be used to assess important community traits that directly and indirectly contribute to the sustainability and resilience of their food-energy-water system. If stakeholders and community members fully access and utilize all the relevant social and economic information to assess the sustainability and resilience of a food-energy-water system, they are more likely to develop a fuller and more accurate understanding of the state of the system and can make better-informed decisions on issues related to sustainability and climate resilience within their communities.

References

- Becker, G. S. (1994). Human capital: A theoretical and empirical analysis, with special reference to education (3rd ed.). Chicago: University of Chicago Press.
- Bourdieu, P. (2011). The forms of capital. In I. Szeman & T. Kaposy (Eds.), Cultural theory: An anthology (pp. 81–93). Hoboken, NJ: Wiley-Blackwell. (Original work published 1986)
- Emery, M., & Flora, C. (2006). Spiraling-up: Mapping community transformation with community capitals framework. *Community Development*, 37(1), 19–35. <https://doi.org/10.1080/15575330609490152>
- Florida, R. (2011). The rise of the creative class. New York: Basic Books.
- Putnam, R. D. (1995). Bowling alone: America's declining social capital. *Journal of Democracy*, 6(1), 65–78. <https://doi.org/10.1353/jod.1995.0002>

A Vulnerability Analysis for the Columbia River Basin's Food-Energy-Water System

Paris Edwards

THE FUTURE OF WATER AND THUS FOOD AND ENERGY PRODUCTION IN THE COLUMBIA RIVER BASIN IS UNCERTAIN. CHANGES TO WATER RESOURCES WILL NOT HAVE EQUAL IMPACT ACROSS FOOD, ENERGY AND WATER SECTORS. WE MAPPED HYDROLOGIC AND SOCIO-ECONOMIC VULNERABILITY TO CHANGES IN WATER RESOURCES ACROSS THE BASIN, A PRODUCT THAT CAN HELP DECISION-MAKERS THINK AHEAD AND TAKE ACTION WITH THE MOST SENSITIVE SUBBASINS IN MIND.

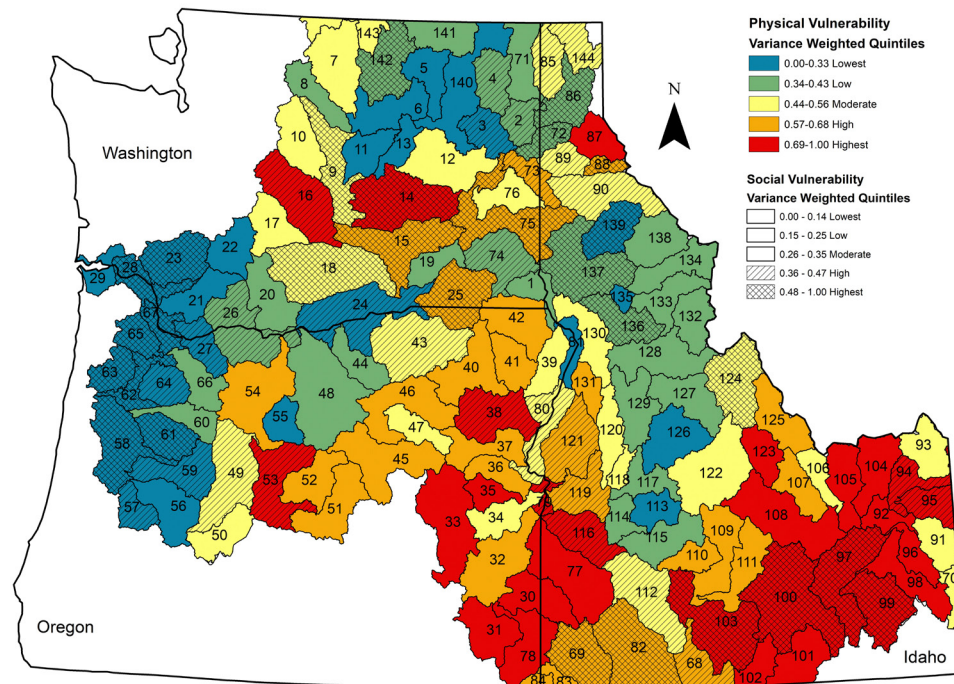


Figure 1. Map of variance weighted vulnerability hotspots. Red coloring and crosshatching indicate overlapping vulnerabilities.

Water systems across the Columbia River Basin sustain crops, livestock, ecosystems, people and power production. These highly managed, interconnected networks of rivers, reservoirs, canals, and pipelines are economic mainstays for the region, and play a foundational role in food and energy security and sustaining natural resource livelihoods. However, climate change has begun to challenge water resources by increasing temperatures, decreasing snowpack, and altering the timing and amount of available water (Mote et al. 2005; Regonda et al. 2005; Nolin and Daly, 2006). Current water management systems are designed around historical norms and trends that are rapidly becoming outdated, due to increasing climate variability and uncertainty about future resources. We now have to reconsider how best to plan around and adapt to expected change in order to reduce and avoid negative consequences to the overall food-energy-water (FEW) system and to community well-being.

Adaptation planning is largely about anticipating future needs in balance with expected change. We recognize that appropriate adaptation strategies to address changes in water resources are specific to a particular place and influenced by many factors, including hydrology and socio-economics. For example, adaptation plans that are appropriate for a rural, agricultural community in the arid eastern portion of the Columbia River Basin should be different from plans for a densely populated, urban community on the wetter west side of the Basin. Our study highlights these social and physical particularities across 144 subbasins in Oregon, Idaho and Washington to improve our understanding of relative vulnerability to water loss at a management-ready scale. The results provide a jumping off point for future, community-scale research and adaptation planning.

To carry out our analysis, we engaged with regional water managers to develop a suite of Basin-relevant social and physical variables indicative of sensitivity to increased water scarcity (Tables 1 and 2). We mapped the results to get a clearer view of subbasins that may be more vulnerable to climate change impacts on water resources (Figure 1).

Table 1. Social vulnerability indicators.

Indicator	Description	Rationale
Age	Per capita population age 5 and under and age 65 and over	Extremes of the age spectrum affect adaptive capacity-increasing “burden of care”
Tenure	Per capita population living in a different house in the US one year ago	May indicate knowledge of place/community network strength and adaptive capacity
Female Head of Household	Per capita households comprised of single women with dependents under 18 years	Higher likelihood of poverty status, lower wages, and family care responsibilities that increase vulnerability to negative impacts from change
Education	Per capita population with a high school education or equivalent	Linked to socio-economics and ability to access and use information related to change/adaptation
Poverty	Per capita population living below 200% of the Federally determine poverty line	Income enables individuals and families to recover from/absorb losses
Renter Occupied Housing	Per capita renter occupied housing	May indicate transience and low financial resources to adapt
Unemployment	Per capita population 16 years and older who are unemployed	Reduced financial resources and adaptive capacity
Natural Resource Economic Dependence	Per capita civil population 16 years and older who are employed in agriculture, forestry, fishing, hunting, and mining	Heavy dependence on natural resource sectors may reduce ability to recover from or adapt to change
Race/Ethnicity	Per capita population identifying as: American Indian or Alaska Native alone, Black or African American alone, and Hispanic or Latino origin (any race)	Minorities have disproportionately reduced access to adaptation information and resources

This approach allows for readily viewing geographic patterns of vulnerability, and identifying “hotspots” of overlapping social and hydrologic vulnerability. We argue that vulnerability hotspots, in particular, may benefit from targeted adaptation resources, such as further study of on-the-ground vulnerabilities, and exploration of community-specific needs.

To determine vulnerability, we compare two simple methods: the equal weighting method and the variance weighting method. Both methods assign a score between 0 and 1 for each vulnerability indicator. These scores are summed to provide a final score for each subbasin and standardized for the sake of comparison. The equal weighting method assumes all indicators contribute equally to the overall vulnerability score, while the variance weighting method uses a statistical approach called a Principle Components Analysis (PCA) that groups the strongest indicators of vulnerability in order of importance. Instead of assuming each indicator contributes equally to vulnerability (e.g. poverty is as important as education), the PCA allows us to assign a specific, numerical amount of importance to each indicator before summing.

Our findings suggest that, of the social variables considered (Table 1), age, poverty and household composition strongly influence overall social vulnerability across the Basin. Additionally, we find that the greatest concentration of highly vulnerable subbasins are located in southern Idaho along the Snake River Plain (Figure 1). We also find that social vulnerability associated with economic dependence on natural resources is most common among rural subbasins, while urban subbasins are more commonly influenced by minority status. The results of our hydrologic vulnerability analysis show similar geographic patterns, with a concentration of highly vulnerable subbasins clustered in eastern Oregon and southeastern Idaho. A high dependence on irrigated agriculture and a dominance of “at-risk snow” elevation ranges strongly influence hydrologic vulnerability in these areas.

Potential “hotspots” of vulnerability are found in subbasins where high social and hydrologic vulnerability co-exist. These hotspots were identified throughout southern Idaho, in eastern Oregon, and in central Washington.

Table 2. Hydrologic vulnerability indicators.

Indicator	Description	Rationale	Data Source(s)
At Risk Snow Area	Proportion of HUC area at 1-2km elevation	Mid elevations are vulnerable rain-snow shift	USGS Digital Elevation Model
Elevation Variance	Variance of mean elevation	Higher mean variance may be a buffer to temperature increases	USGS Digital Elevation Model
Flow Variability (April-Sept)	Coefficient of variation of average monthly streamflow	Provides variation and trend	USGS WaterWatch
Winter Temperature	Annual coefficient of variation	Provides variation and trend	PRISM
Winter Precipitation	Annual coefficient of variation	Provides variation and trend	PRISM
Water Quality	Percent of total stream miles designated as “impaired”	Impairment is expected to worsen and spread	EPA ATTAINS Program
Land Ownership	Proportion of HUC area in non-public ownership	Ease of policy and management change	Bureau of Land Management
Aquifer Permeability	Proportion of HUC with low permeability	Higher permeability indicates greater likelihood of groundwater storage buffer	USGS PROSPER
Dam Storage	Max storage of dams over 50ft per HUC	Higher storage capacity indicates greater likelihood of buffer to loss/variability	US Army Corps of Engineers National Dams Inventory
Irrigated Agriculture	Proportion of HUC in irrigated agriculture	High irrigated ag indicates high use and dependence on seasonal fresh water	USGS PROSPER

Two standout subbasins, American Falls and Portneuf in southeastern Idaho, show high overlapping social and physical vulnerability scores across both of our comparative methods. These subbasins are home to two of the state’s largest population centers, intensive agricultural production, small-scale power production, and the Fort Hall Native American Reservation. This overlap of social and hydrologic vulnerability suggests the possibility of lower potential social capacity to adapt, coupled with higher potential likelihood of water loss and increased variability.

As the Columbia River Basin’s climate changes and FEW resources change with it, some subbasin communities will be affected more than others. The importance of moving forward with localized adaptation planning cannot be over-emphasized. Our vulnerability map can help communities and their leaders be better informed and more nimble in their efforts to think ahead and take action with the most sensitive subbasins and their communities in mind.

References

- Mote, P. W., Hamlet, A. F., Clark, M. P., & Lettenmaier, D. P. (2005). Declining mountain snowpack in western North America. *Bulletin of the American meteorological Society*, 86(1), 39.
- Nolin, A. W., & Daly, C. (2006). Mapping “at risk” snow in the Pacific Northwest. *Journal of Hydrometeorology*, 7(5), 1164-1171.
- Regonda, S. K., Rajagopalan, B., Clark, M., & Pitlick, J. (2005). Seasonal cycle shifts in hydroclimatology over the western United States. *Journal of Climate*, 18(2), 372-384.

Dr. Eva K. Strand (Associate Professor of Rangeland Ecology and Management in the Department of Forest, Rangeland and Fire Sciences at the University of Idaho) was the author’s doctoral advisor, co-author on the forthcoming publication of this work, and played a strong supporting role in the research.

Managing For Whom? Social Well-Being and the Food-Energy-Water System of the Columbia River Basin

Michael Briscoe and Jennifer E. Givens

AVAILABILITY OF NEW, LARGE DATASETS HAS EXPANDED POSSIBILITIES FOR RESEARCH IN SOCIO-ECOLOGICAL SYSTEMS AND, ALONG WITH FOCUS GROUPS OF STAKEHOLDERS, CAN HELP INFORM WHICH ASPECTS OF THE FOOD-ENERGY-WATER (FEW) SYSTEM ARE MOST IMPORTANT FOR DRIVING RESOURCE USE AND INFLUENCING SUSTAINABLE OUTCOMES, BOTH IN GENERAL AND FOR SPECIFIC GROUPS AND CONTEXTS.

Whenever we discuss sustainability or resilience, we need to ask “sustainability (or resilience) for whom?” Building resilience or sustainability for some is a lackluster achievement if it comes at the expense of other users, specific groups within society, or society in general. Research also often conceptualizes biophysical systems and social systems as distinct and disconnected, and focuses on separate parts rather than how these parts fit together as a connected system. Recently, researchers and managers have begun to frame social and biophysical systems as connected socio-ecological systems. With this approach, it is evident that social variables are both outcomes and drivers in socio-ecological systems (Givens et al. 2018), and that natural resource decisions are tied to social well-being.



Figure 1. Inside Rocky Reach Dam, one of the Columbia River dams that facilitated economic expansion and inexpensive power, yet also impact salmon populations.

Social Outcomes

Whether discussed explicitly or not, natural resource management decisions almost always impact society in complex ways. Sometimes natural resource industries can have negative impacts on communities, as with the boom and bust cycles of energy towns (Freudenburg 1984), where the increased depression, suicide, delinquency, mental disorders, and other social problems that came to energy boomtowns were characterized as “Gillette Syndrome” (Smith et al. 2001). However, research shows that in some contexts towns can recover after boom periods subside.

On the other hand, natural resource development can have positive social impacts as well. Some communities actively seek industries for the economic development they can bring, even knowing they are environmentally damaging. This could apply to the Columbia River Basin when the dams were built in the 1930s and beyond, facilitating economic expansion in the Pacific Northwest and providing inexpensive power (Figure 1). Governments and managers now must grapple with the impacts of dams on salmon. Native American tribes, which relied on salmon populations, are losing both a source of food and cultural heritage. Furthermore, in some cases their burial grounds were flooded by newly created reservoirs before they could move the individuals buried there, a loss mourned by both the tribes and archeologists and anthropologists.

In addition to the Columbia River Basin's abundant hydropower and expansive river system, the region is also important for its food production. The major agricultural products for the region include wheat, potatoes, apples, pears, and dairy (USDA 2019). Farms and the production methods they employ can have far-reaching community impacts, both positive and negative. Local food can promote social interaction, and keep money within communities, but some forms of intensive food production can have detrimental economic impacts and create pollution that has negative impacts on health and quality of life of local residents.

Social Drivers

Communities can shape natural resource use and production. Sociologists developed the IPAT equation (Impact = Population, Affluence, and Technology) that gives a general starting point for conceptualizing social drivers of environmental outcomes (York et al. 2003). How these different factors work and impact environmental outcomes varies by context, and requires additional research to understand their nuances. Adaptive governance and adaptive management are approaches to natural resource management that take these different contexts into consideration by bringing local people and organizations into the governance and resource management processes, and building resilience as more community members become involved in management and are able to better respond to uncertainties and shocks to the system (Chaffin et al. 2014). As stakeholders are actively included in the research process through focus group interviews, they can help identify important social drivers that warrant further analysis, and help identify social outcomes that are impacted by decisions within the food-energy-water system and that could be incorporated into management planning.

Moving Forward

Existing efforts that incorporate social elements into food, energy and water research tend to focus on the micro-scale, looking at specific communities or case studies. This research is valuable, but may not be applicable to other communities or managers making resource decisions. The new availability of large datasets may help address these and other challenges in socio-ecological systems research. Our research strives to use "big data" to identify generalizable patterns across contexts, while also keeping the unit size small enough to see patterns at local levels. We are beginning to use such data to analyze relationships between social well-being, food, energy, and water consumption, production and management indicators at the county level. Our analyses of these data are intended to reveal patterns in both the social outcomes of natural resource use decisions and the social factors that drive such decisions. Through focus group interviews, stakeholders and community members can help identify key variables, and provide context and greater understanding of what these patterns mean in practice for resource managers and for the well-being of local areas.

References

- Chaffin, B., Gosnell, H., & Cosens, B. A. (2014). A decade of adaptive governance scholarship: synthesis and future directions. *Ecology and Society*, 19(3).
- Freudenburg, W. R. (1984). Boomtown's youth: The differential impacts of rapid community growth on adolescents and adults. *American Sociological Review*, 697-705.
- Givens, J. E., Padowski, J., Guzman, C. D., Malek, K., Witinok-Huber, R., Cosens, B., Briscoe, M., Boll, J., & Adam, J. (2018). Incorporating social system dynamics in the Columbia River Basin: Food-energy-water resilience and sustainability modeling in the Yakima River Basin. *Frontiers in Environmental Science*, 6, 104.
- Smith, M. D., Krannich, R. S., & Hunter, L. M. (2001). Growth, decline, stability, and disruption: A longitudinal analysis of social well-being in four western rural communities. *Rural Sociology*, 66(3), 425-450.
- USDA (2019). Agriculture in the Northwest. *United States Department of Agriculture: Climate Hubs*. Retrieved on May 28, 2019 from <https://www.climatehubs.oce.usda.gov/hubs/northwest/topic/agriculture-northwest>
- York, R., Rosa, E. A., & Dietz, T. (2003). Footprints on the earth: The environmental consequences of modernity. *American Sociological Review*, 279-300.

Understanding Interactions Between Food Production, Water Management and Water Quality in the Yakima River Basin

Sammi Grieger and John Harrison

IN WATER-STRESSED, INTENSIVELY MANAGED AGRICULTURAL VALLEYS LIKE THE YAKIMA RIVER BASIN, SUSTAINABLY MANAGING FOOD PRODUCTION SYSTEMS AND AQUATIC ECOSYSTEMS REQUIRES AN UNDERSTANDING OF THE RELATIONSHIPS BETWEEN WATER FLOWS AND NUTRIENT FLUXES OVER MULTIPLE DECADES. OUR WORK AIMS TO FURTHER DEVELOP THIS UNDERSTANDING THROUGH ANALYSIS AND SYNTHESIS OF HISTORICAL DATA.

Understanding trade-offs between the food, energy and water sectors and environmental quality in the Yakima River Basin is important in developing future management that sustains and preserves FEW resources. Focusing on trade-offs between the Yakima's food and water sectors is especially meaningful, as the Basin leads Washington State in orchard and milk production, and is the nation's largest producer of apples, cherries and hops (USDA 2017). Fruit, corn and other high-value crops grown in the Yakima Basin require a consistent water supply in order to meet agricultural demands, meaning over 180,000 hectares are irrigated annually (Vano et al. 2010). The main source of water to support irrigation demands in the Yakima Basin is surface water diverted from the Yakima River. This surface water comes mostly from snowmelt in the spring and early summer, and five primary storage reservoirs in the mountains store 30% of the Basin's annual runoff, helping to provide water for downstream irrigation when needed later in the growing season (USBR 2002).

Over the past century, the Yakima Basin has seen rapid increases in population (Figure 1) and agricultural intensification. Agricultural and urban activities are significant sources of nutrients, such as nitrogen (N) and phosphorus (P), which can enter waterways via runoff and potentially harm water quality (Figure 2). Inputs of N and P have been increasing in the Yakima watershed (Figure 3), and elevated levels of N and P have been measured in surface waters and groundwater. For example, an assessment by federal, state, and local agencies found that over 2,000 people obtain water from wells with N concentrations above the Environmental Protection Agency's drinking water standard (10mg NO₃-N/L) (WSDE, 2010), initiating further assessments of N in groundwater in the lower Yakima (Bahr et al. 2018). Average N and P concentrations in the Yakima River are enriched relative to unpolluted surface waters.

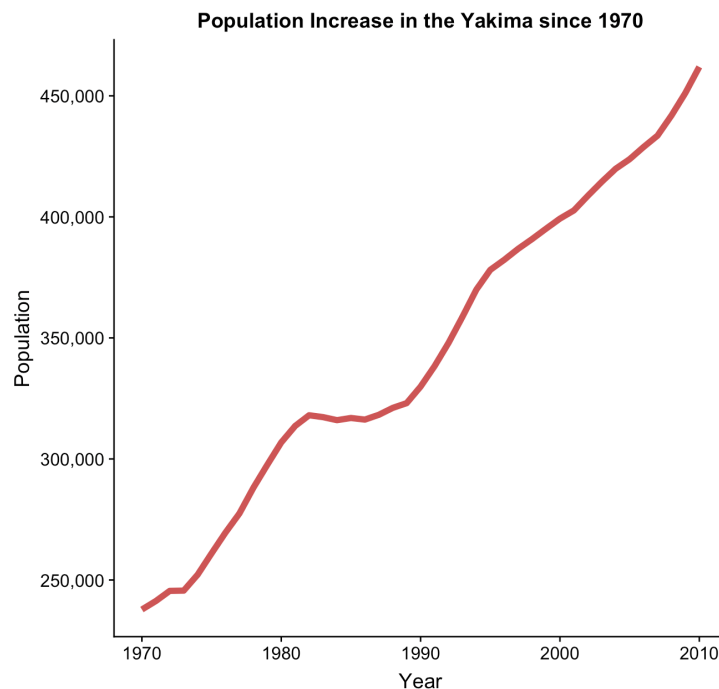


Figure 1. Total populations of Benton, Kittitas, & Yakima counties from 1970 to 2010. Data from U.S. Census Bureau.

In addition to water quality concerns, the Yakima faces water supply concerns. The Yakima water system has been over-appropriated, and particularly during dry years, some water rights holders do not receive their full allotments (ECONorthwest 2017). Strains on water supply for irrigation needs highlight potential friction points between agricultural water use and water quality. As water is diverted from the river for irrigation, less water is available to dilute incoming N or P from agriculture runoff. Similarly, if irrigation needs increase, the amount of pollutants entering the river via return flows could increase, risking water quality degradation. In light of the emerging stresses on water resources and potential trade-offs between agricultural water use and water quality in the Yakima, it is important to understand how water management influences instream flows, and N and P fluxes in the watershed. Understanding how past management decisions have influenced nutrient fluxes is necessary for managers to find a balance between maintaining agricultural operations and sustaining ecosystem functions.

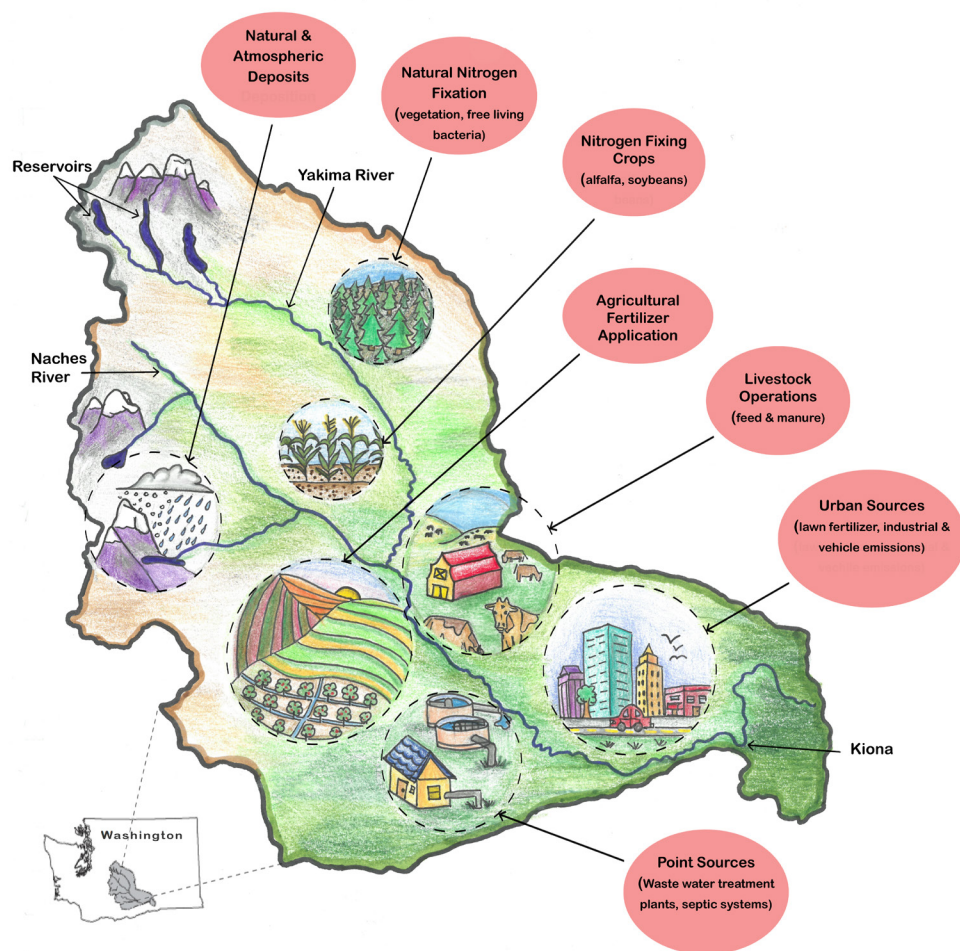


Figure 2. Diagram of the Yakima River Basin, describing the major sources of nutrients to the Basin from human and natural activities across the watershed. Diagram includes the five major storage reservoirs located in the upper Yakima, the Yakima and Naches rivers, as well as Kiona, a gage station on the lower Yakima River where long-term nutrient data is from. Inputs of nutrients, such as nitrogen (N) or phosphorus (P), shown are: atmospheric nitrogen deposition, natural biological nitrogen fixation, agricultural nitrogen fixation from crops such as legumes, fertilizer application (both agricultural and urban), livestock operations, emissions from urban activities, and point source inputs from waste water treatment plants, septic waste or runoff.

We are analyzing and synthesizing records of water flow and nutrient loads in the Yakima Basin watershed to investigate interactions between water flow and N and P exports. To better understand historical nutrient management, we are using county-level U.S. Department of Agriculture Census and fertilizer sales data to estimate annual N and P inputs to the Basin. Agricultural nutrient inputs from fertilizer application have increased over 80-fold (N) and 10-fold (P) since 1945 (Figure 3). Nutrients from manure and livestock operations have increased as well, albeit not as rapidly as fertilizer loads. Interestingly, increasing nutrient inputs have not been accompanied by comparable rapid increases in river nutrient exports. A long-term dataset of daily nitrate and phosphate loads at Kiona, a site close to the mouth of the Yakima River, shows no clear trend in river loads over time (Figure 4).

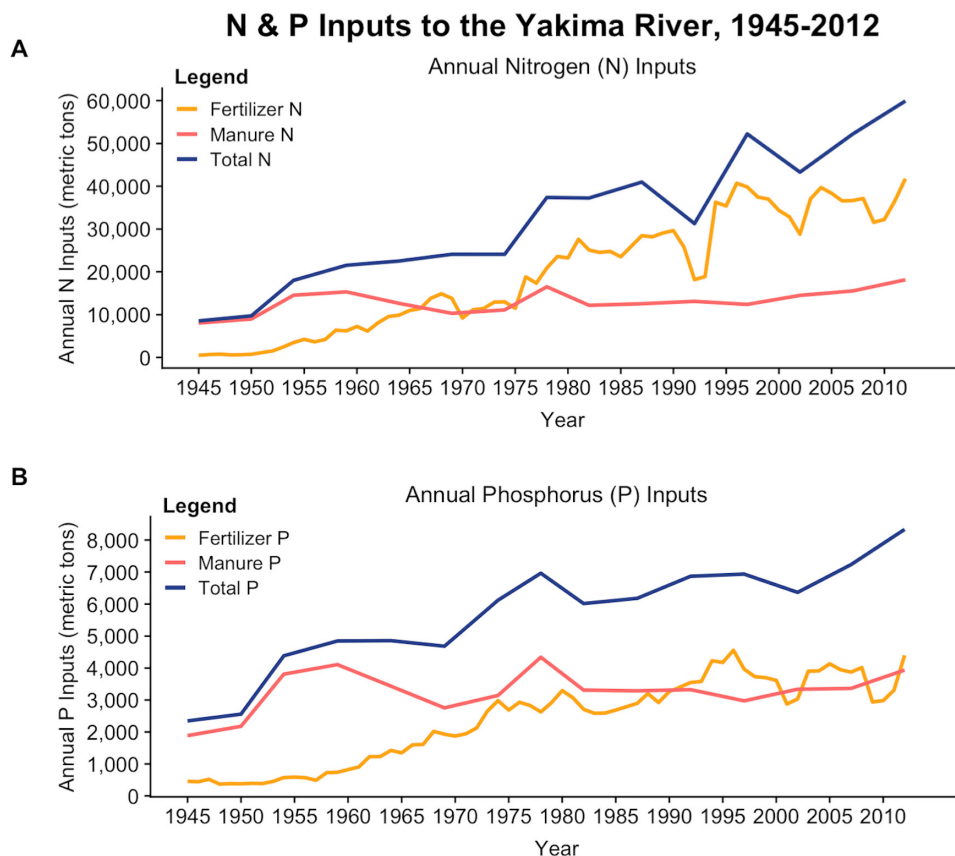


Figure 3. Annual inputs of A) nitrogen (N) and B) phosphorus (P) for the Yakima Basin from 1945 to 2012. Blue line represents total inputs, pink line represents inputs from manure, and yellow line represents inputs from fertilizer. Data from U.S. Department of Agriculture, Alexander and Smith (1990), Ruddy et al. (2006), and Brakebill and Gronbery (2017).

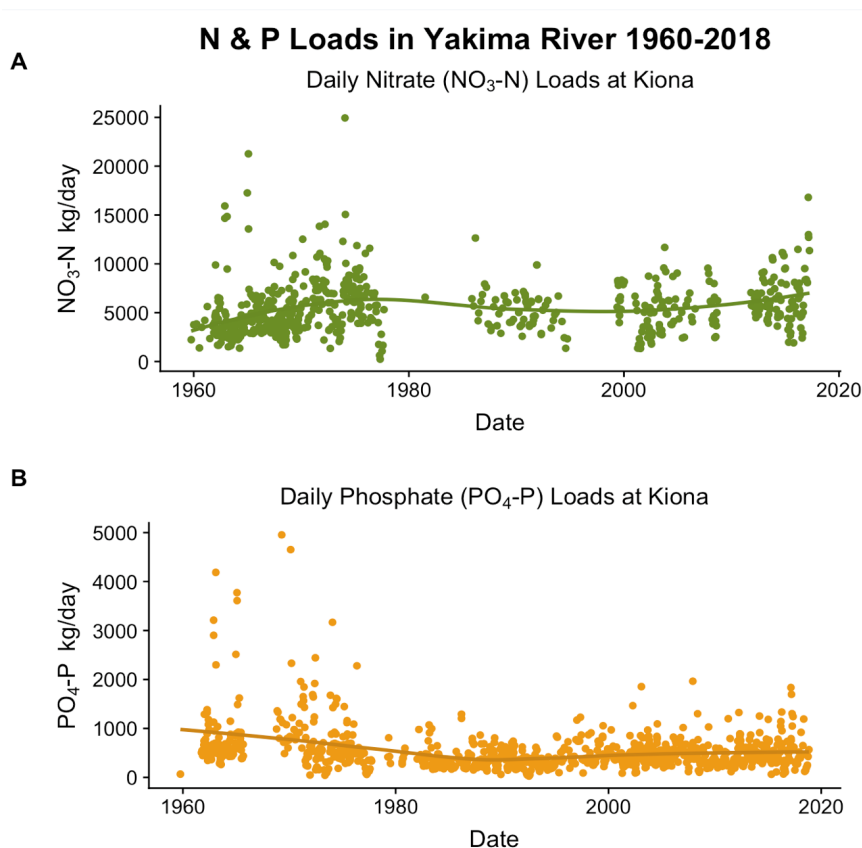


Figure 4. Historical daily loads (kg/day) of A) nitrate (NO_3^-) and B) phosphate (PO_4^{3-}) in the Yakima River at Kiona. Data from USGS (2018) and WSDE (2018).

This apparent lag between trends in Basin nutrient inputs and river nutrient exports over the last 70 years raises questions about the fate of the “missing” N and P, such as:

- 1) Where has it gone? Is it accumulating in the soil or groundwater, or in the case of N, it is being lost to the atmosphere (i.e. denitrified) via microbial activity?
- 2) Is this apparent imbalance likely to continue, or if N and P are accumulating, will it eventually begin leaking into surface waters at greater rates?
- 3) Are there ways—for example, by manipulating reservoir water releases—we can manage water and nutrients so as to mitigate current or potential water quality problems associated with agricultural intensification in the Basin?

These are the questions we are looking to answer. Understanding the drivers of nutrient loading may help identify management strategies to ease the challenge the Yakima Basin is facing, to preserve water quality while simultaneously adapting to a changing climate and its growing agricultural economy. Insights from the Yakima Basin may also inform a broader understanding of stresses and trade-offs facing FEW systems in arid, agricultural valleys throughout the American West and beyond.

References:

- Alexander R.B. and Smith R.A. 1990. County-level estimates of nitrogen and phosphorus fertilizer use in the United States, 1945 to 1985. U.S. Geological Survey (USGS) Open-File Report 90-130. <http://doi.org/10.3133/ofr90130>
- Bahr G, P. Beale, M. Drennan, J. Hancock, K. McLain, C. Kozma, M. Martian, V. Redifer. 2018. Estimated Nitrogen Available for Transport in the Lower Yakima Valley Groundwater Management Area. WSDA and Yakima County, agr.wa.gov/FP/Pubs/NaturalResourcesAssessmentPubs.aspx
- Brakebill, J.W. and Gronberg, J.M. 2017. County-Level Estimates of Nitrogen and Phosphorus from Commercial Fertilizer for the Conterminous United States, 1987-2012: USGS data release, <https://doi.org/10.5066/F7H41PKX>.
- ECONorthwest. 2017. Water Security for the Yakima River Basin's Economy, Communities and Watersheds. Portland, Oregon. Ecology Publication Number 17-12-009.
- Ruddy B.C., D.L. Lorenz, D.K. Mueller. 2006. County-Level Estimates of Nutrient Inputs to the Land Surface of the Conterminous United States, 1982–2001. USGS Scientific Investigations Report 2006-5012, 17p.
- U.S. Department of Agriculture (USDA). 2012. Census of Agriculture Historical Archive. Washington D.C. <http://agcensus.mannlib.cornell.edu/AgCensus/homepage.do>
- USDA, National Agricultural Statistics Service. 2017. NASS - Quick Stats. USDA National Agricultural Statistics Service, accessed [May 6, 2019], at URL [<https://data.nal.usda.gov/dataset/nass-quick-stats>]
- USDA, National Agricultural Statistics Service - Northwest Regional Office. 2018. 2018 Washington Annual Statistical Bulletin. https://www.nass.usda.gov/Statistics_by_State/Washington/Publications/Annual_Statistical_Bulletin/2018/WA_annual%20bulletin%202018.pdf
- U.S. Census Bureau. Population Division. 1940-2010, accessed Apr 1, 2019, at URL <https://www.census.gov/data/tables.html#>.
- U.S. Department of the Interior; Bureau of Reclamation. 2002. Interim Comprehensive Basin Operating Plan for the Yakima Project Washington. Yakima, Washington.
- USGS. 2018. National Water Information System data available on the World Wide Web (Water Quality Samples for USA: Sample Data), accessed [Dec 4, 2018], at URL [<https://nwis.waterdata.usgs.gov/nwis/qwdata?>].
- Vano, J.A., M.J. Scott, N. Voisin, C.O. Stöckle, A.F. Hamlet, K.E.B. Mickelson, M.M.G. Elsner, and D.P. Lettenmaier. 2010. Climate Change Impacts on Water Management and Irrigated Agriculture in the Yakima River Basin, Washington, USA. *Climatic Change* 102:287–317.
- Washington State Department of Ecology (WSDE). 2018. Freshwater Information Network data available on the World Wide Web (River and Stream Water Quality), accessed [Jan 30, 2019], at URL [<https://apps.ecology.wa.gov/eim/search/Default.aspx>]
- WSDE, Washington State Department of Agriculture, Washington State Department of Health, The Yakima County Public Works Department, Environmental Protection Agency (US). 2010. Lower Yakima Valley Groundwater Quality: Preliminary Assessment and Recommendations Document. Olympia, WA: Washington State Department of Ecology. Publication No. 10-10-009.

Improving Agricultural Nitrogen Use Efficiencies from Farm to Regional Scales: Trade-offs among Food, Energy and Water Sectors

Mingliang Liu, Jennifer C. Adam and Claudio O. Stöckle

UNDERSTANDING AGRICULTURAL NITROGEN USE AT MULTIPLE SCALES CAN HELP PRODUCERS CHOOSE THE RIGHT TIME, LOCATION, AND AMOUNT OF NITROGEN TO APPLY, IMPROVING NITROGEN USE EFFICIENCY (NUE), AND THE OVERALL SUSTAINABLE MANAGEMENT OF THE FOOD-ENERGY-WATER SYSTEM IN THE COLUMBIA RIVER BASIN.

More than half of the world's food is produced through modern, intensively managed agriculture. Such production cannot be sustained without using synthetic nitrogen (N) fertilizer. Widespread use of N fertilizer has greatly increased crop yield in nutrient-deficient soils. However, there are trade-offs. Fertilizer manufacture is an energy-intensive industry, using about 1.2% of the world's energy, mostly for N-based fertilizer (International Fertilizer Industry Association 1998). Agriculture also plays a major role in water pollution: over-fertilization of crops leads to excess N in the agricultural ecosystem (roughly 50-60%; Conant et al. 2013). N in the form of nitrate (NO_3^-) can either run off into rivers and lakes, posing risks of eutrophication and fish kills, or leach into and contaminate groundwater, potentially polluting drinking water sources. Additionally, N can be transformed to nitrous oxide (N_2O), an important greenhouse gas that is roughly 300 times more potent than carbon dioxide and can also deplete stratospheric ozone (Figure 1).

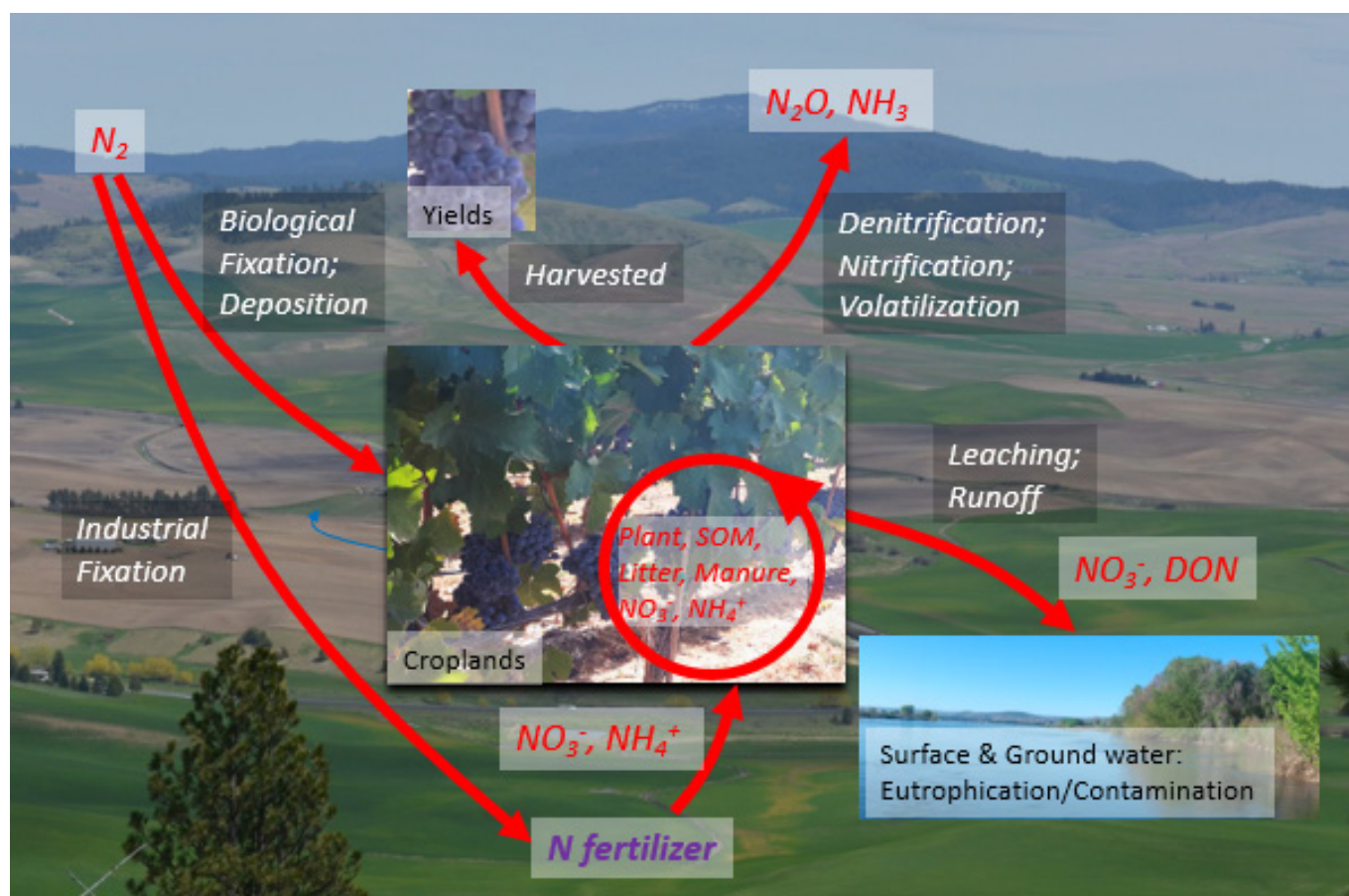


Figure 1. Main sources and possible destinations of agricultural nitrogen fertilizer. More detailed descriptions of the nitrogen cycle in natural and agricultural systems can be found in Chapin et al. (2002) and Vitousek et al. (2013) (SOM: soil organic matter; DON: dissolved organic nitrogen; NO_3^- and NH_4^+ : inorganic nitrogen [N] forms available for plant uptake; N_2O : a greenhouse gas that can deplete stratospheric ozone).

Nitrogen use efficiency (NUE) is defined as the ratio of N recovered in harvested products (grains, fruit, etc.) relative to the N inputs (synthetic fertilizers, manure, symbiotic fixation and atmospheric deposition). Higher NUE implies

that relatively more N is enhancing crop production and less N is leaving the system which causes environmental degradation. As such, NUE has been used as an important indicator of sustainability (SDSN 2015; Zhang et al. 2015). In order to increase crop yields to meet our growing population's needs while protecting the environment, it is critical to optimize the trade-offs between agricultural N inputs and N exports at multiple spatial scales. It is important to understand differences between the trade-offs an individual farm or small irrigation district may face and the trade-offs a state or nation faces. NUE varies significantly among regions and countries due to differences in soil types, climate, and farming practices, and the cost and benefit of NUE improvement itself also varies depending on technology and local socio-economic and biophysical conditions. Improved agronomic practices can increase NUE potential, and therefore change the N input-yield relation, that is, the trade-offs between applying more N and increasing excess N in the system, as well as the trade-offs between N fertilizer use and increased energy use and irrigated water demand. This is also known as the N trade-off frontier: obtaining more harvested N with same N input (Tilman et al. 2002; Mueller et al. 2017) (Figure 2).

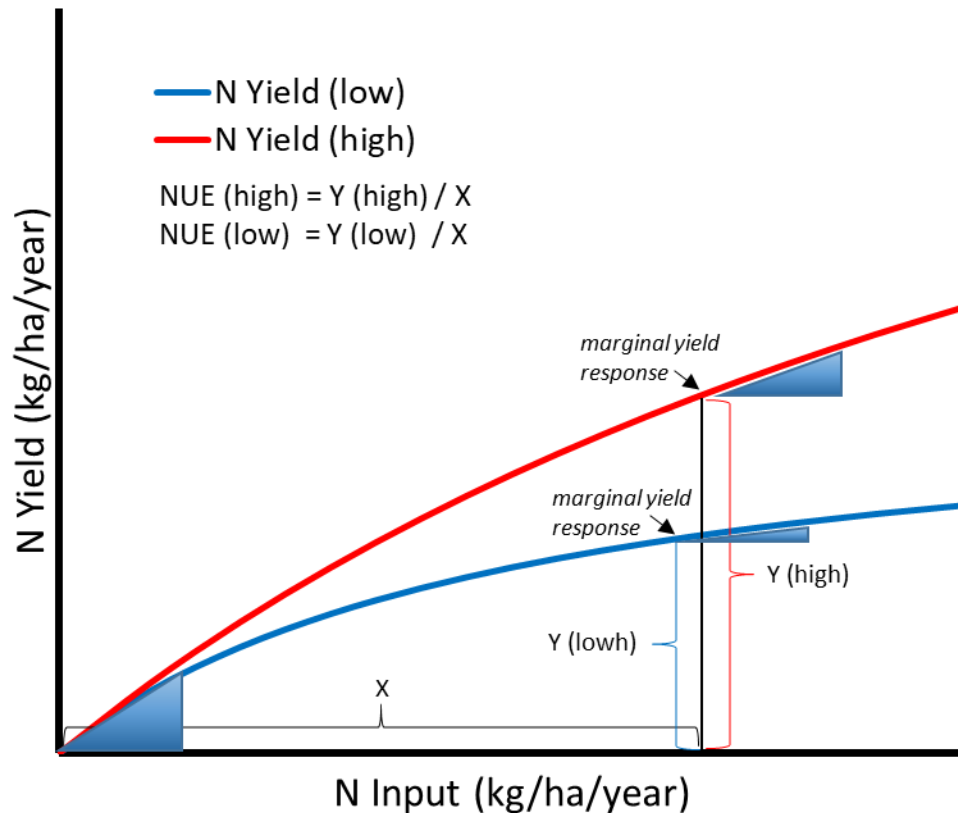


Figure 2. Concept of N input-yield relation (N trade-off frontier) under low- and high-level of agronomic practices (adapted from Mueller et al. 2017). The x-axis shows total N fertilizer use; the y-axis shows total harvested N; the blue and red lines represent the response curves of harvested N in response to fertilizer use in low-level and high-level agronomic practices, respectively; the triangles with different slopes represent the response of N yield to N application at specific N application levels for that agronomic practice.

By quantifying the patterns of NUE across the Columbia River Basin we will lay the foundation for efforts to improve this sustainability metric across our region, and for evaluating the effectiveness of such improvements. Our specific objectives are to:

- 1) Quantify the patterns of field-scale variations in NUE across different climatic zones, under different farming practices and crop rotations, as well as its dynamics given year-to-year variations in weather;
- 2) Quantify the NUE at county and state levels in economic terms, such as income from crop yield and its relationship to total N input; and
- 3) Estimate the N budget of agricultural ecosystems under current and projected climate and land use change scenarios.

We will integrate field observations, survey data, outputs from a watershed-scale, crop growth and nutrient transport model (MicroBasin) and a macro-scale, coupled hydrological and crop growth model (VIC-CropSyst) (Box 1) to reconstruct N fluxes between agricultural ecosystems and the atmosphere, N lost through runoff and leaching, and N harvested in crop yields, as well as the movement of N across landscapes with complex terrains. The MicroBasin model is targeted at farm-level precision farming practices and focuses on the local topography and soil type effects on NUE and N. It will be used for case studies and sensitivity analyses in determining how agronomic practices affect NUE on various hillslopes. Meanwhile, VIC-CropSyst focuses on large-scale patterns and helps in regional decision-making processes, and will be used to estimating how NUE can be improved across various climate zones and under climate change scenarios, and through intra-regional trading. This combination of approaches will allow us to provide field-validated estimates of NUE across the whole Columbia River Basin under current conditions, and to explore how a key metric of sustainability varies across the region. It will also allow us to estimate how realistic variations in NUE could affect the overall sustainability and resilience of the food-energy-water system, as well as allowing us to explore the potential for improving NUE using current and emerging agricultural technologies and institutional innovations.

Box 1: Approaches That Will be Integrated in This Study

Field observations provide long-term and continuous observations and experiments on N content in soils, fertilizer N input, N harvested in crop yields, and N leaching at field, station and watershed scales.

Survey data include information on synthetic fertilizer production, crop yield, manure production and application. These kinds of surveys are mostly being conducted at county and state levels.

The **MicroBasin model** is a three-dimensional, watershed-level crop growth model in which core plant growth, management, and soil biogeochemical processes are simulated with CropSyst (Stöckle et al. 1994; Ward et al. 2018). MicroBasin then simulates water and N transport vertically through the soil profile and horizontally across the whole watershed.

The **VIC-CropSyst model** is a macro-scale hydrological and crop growth model which couples the Variable Infiltration Capacity (VIC) model and the CropSyst model (Liang et al. 1994, 1996; Malek et al. 2017). The integrated model calculates a closed water and energy budget over all biome types, and tracks the N fluxes and the impacts of management practices (e.g. irrigation, fertilization, tillage, grazing, harvest, and rotation) on cropland and pasture. We are using remotely sensed data (gross and net primary production and evapotranspiration estimates based on MODIS satellite data) and data from US Geological Survey stream gages to validate the modeled results.

References:

- Chapin, F.S., Matson, P.A., Mooney, H.A., 2002. Principles of terrestrial ecosystem ecology. Springer-Verlag, New York, USA.
- Conant, R.T., Berdanier, A.B., Grace, P.R., 2013. Patterns and trends in nitrogen use and nitrogen recovery efficiency in world agriculture. *Glob. Biogeochem. Cycles* 27, 558–566. <https://doi.org/10.1002/gbc.20053>
- Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A., 2008. Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science* 320, 889–892. <https://doi.org/10.1126/science.1136674>
- International Fertilizer Industry Association, 1998. The fertilizer industry, world food supplies and the environment.
- Knowles, R., 1982. Denitrification. *Microbiol. Rev.* 46, 43–70.
- Leadership Council of the Sustainable Development Solutions Network (SDSN), 2015. Indicators and a Monitoring Framework for Sustainable Development Goals—Revised Working Draft.
- Mueller, N.D., Lassaletta, L., Runck, B.C., Billen, G., Garnier, J., Gerber, J.S., 2017. Declining spatial efficiency of global cropland nitrogen allocation. *Glob. Biogeochem. Cycles* 31, 245–257. <https://doi.org/10.1002/2016GB005515>
- Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. *Nature* 418, 671–677. <https://doi.org/10.1038/nature01014>
- Vitousek, P.M., Menge, D.N.L., Reed, S.C., Cleveland, C.C., 2013. Biological nitrogen fixation: rates, patterns and ecological controls in terrestrial ecosystems. *Philos. Trans. R. Soc. B-Biol. Sci.* 368. <https://doi.org/10.1098/rstb.2013.0119>
- Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. *Nature* 528, 51–59. <https://doi.org/10.1038/nature15743>

Stream Temperature Modeling in the Columbia River Basin

Nigel Pickering

SALMON IN THE COLUMBIA RIVER BASIN ARE AN ICONIC SPECIES THAT HAVE BEEN TREASURED BY NATIVE AMERICAN TRIBES AND OTHER PEOPLE IN WASHINGTON FOR DECADES. DAMS FOR ENERGY GENERATION, IRRIGATION AND CLIMATE CHANGE HAVE RAISED STREAM TEMPERATURES TO LETHAL VALUES FOR SALMON. WE ARE DEVELOPING A RIVER MODEL THAT WILL BE USEFUL IN DETERMINING THE BEST LAND AND RIVER MANAGEMENT OPTIONS FOR LOWERING STREAM TEMPERATURES TO PROTECT AND PROMOTE THE SURVIVAL OF THE SALMON.

Stream temperatures in the Columbia River Basin have been rising slowly since the early 1900s. A relatively recent evaluation by the Environmental Protection Agency (EPA 2018a) showed about a 4°C (7.2°F) rise in summer stream temperatures since 1970, with about half attributable to dams and half to climate change. Irrigation and hydroelectric dams built in the mid-1900s (such as the Grand Coulee Dam, Figure 1), have slowed down the river and expanded the water surface, both factors that increase stream temperature. Basin modeling research has shown that stream temperatures have increased and will continue to increase with climate change over the next 70 years (Mantua et al. 2010).



Figure 1. Grand Coulee Dam on the Columbia River (Photo: U.S. Bureau of Reclamation, public domain). Water released through the left and right power plants is cooler than that released through the third power plant, which could be used to help manage stream temperatures.

Stream temperature is increasingly a limiting factor to the survival and recovery of many salmonids in the Columbia River Basin, including salmon and steelhead stocks that are listed under the Endangered Species Act. Returning adult sockeye salmon were decimated by extremely high temperatures in 2015. The 2015 year may be a harbinger of a future with more stressful stream temperatures for salmonids, especially during their migration season.

Are there ways that the Columbia River Basin can be managed to ameliorate these stream temperature increases? Peak steelhead and fall chinook runs coincide with the highest stream temperatures in the summer (Figure 2). Can the timing of these high stream temperatures be altered? Migrating fish in the Basin seek out cooler water in the mouth

of tributaries and in the deeper waters of the mainstem. Can we take advantage of this adaptive behavior? Upstream land use management can have serious effects on downstream habitat and stream temperature (Simenstad et al. 1992). Can land conservation or increased recharge promote cooler baseflows? Prior studies have also indicated there could be significant cooling far downstream from releases of cool water from deep outlets at Grand Coulee (EPA 1971; Vermeyen 2000). Can we take advantage of this upstream cooler water by changing dam management?

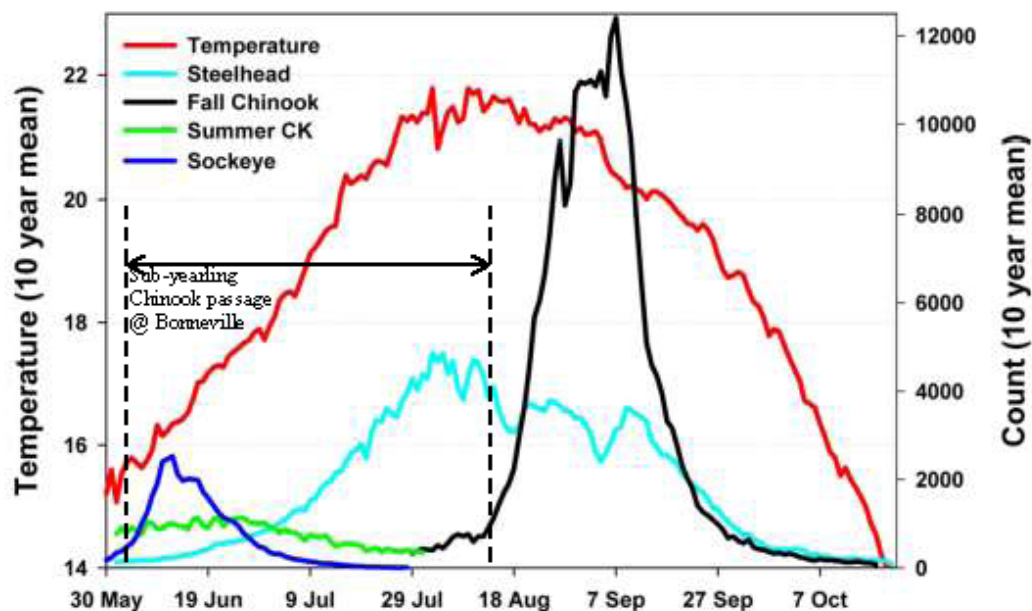


Figure 2. Average stream temperature (°C) at Bonneville Dam (1996-2005) versus fish species count (Keefer, et al., 2008, Marcove et al. 2018) showing how stream temperature affects the run timing of adult salmonid species.

The Columbia FEW project represents the ideal environment for evaluating the effect of land and dam management on stream temperature, but to do that we need an appropriate stream temperature model. Our first step was a review of the stream temperature literature, including regulatory criteria and standards, data availability, and modeling. The intent of this review was to identify suitable models to explore stream temperature questions in the Columbia River Basin, regional data that could be used to calibrate those models, and potential strategies to mitigate the impact of increasing stream temperature on fish species. We now intend to move on to stream temperature modeling.

Prior Models

The most comprehensive stream temperature model is the recently-updated RBM10 model (EPA 2001; EPA 2003; EPA 2018b). This one-dimensional model predicts stream temperature along the river length, ignoring variations in temperature with depth and width. This model was used to evaluate various river management scenarios (EPA 2018c) necessary to develop a stream temperature total maximum daily load (TMDL) for the Columbia and Snake Rivers (Figure 3). When finalized, the TMDL will specify changes in watershed and river management that could achieve acceptable stream temperature targets. Other candidate models that predict stream temperature with depth are a multi-layered CE-QUAL-2W water quality model (PSU, 2018) and a two-layered reservoir module (Niemeyer et al. 2018).

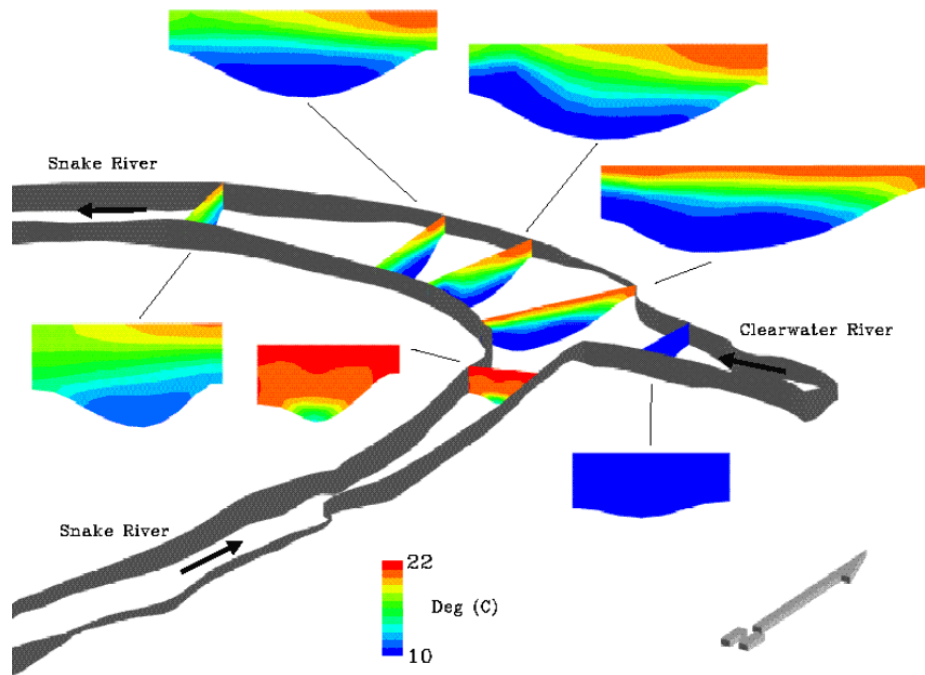


Figure 3. Modeled water temperature for the Clearwater River and Snake Rivers (PNNL, 2017), showing how stream temperature varies with depth.

Existing Data

Stream temperature data have been collected for a long time in the Columbia River Basin. An early assessment of these data found 110 existing stream temperature gages (McKenzie and Laenen 1998), and data sources are now more numerous. Recently, the NorWEST Stream Temperature Database (2018) collated these data, providing one central repository. However, there are still many data gaps, most of the data are from the summer, and many sites have a short record.

Research Strategies

We plan to update the most recent version of the RBM10 model and investigate adding a simple two-layer component to allow the prediction of cooler water with depth. We will work closely with the NorWEST data to collate a ten-year period of good stream temperature to calibrate the model. We can then run the outputs of the Columbia FEW's management scenarios and innovations to predict their impacts on stream temperatures. This will allow us to evaluate how best to manage the land and river system in the Columbia River Basin to enhance the viability of migratory fish populations in the face of rising stream temperatures.

References

- EPA, 1971. Columbia River Thermal Effects Study. Volume 2: Temperature Prediction. EPA Region 10, Seattle, Washington.
- EPA, 2001. Application of a 1-D Heat Budget Model to the Columbia River System. EPA 910-R-01-004. EPA Region 10, Seattle, Washington.
- EPA, 2003. Developing a Temperature Total Maximum Daily Load for the Columbia and Snake Rivers: Simulation Methods. EPA Region 10, Seattle, Washington.
- EPA, 2018a. Assessment of Climate Change Impacts on Temperatures of the Columbia and Snake Rivers—Draft. EPA Region 10, Seattle, Washington.
- EPA, 2018b. Update of the RBM10 Temperature Model of the Columbia and Snake Rivers—Draft. Prepared by TetraTech. EPA Region 10, Seattle, Washington.
- EPA, 2018c. Assessment of Impacts to Columbia and Snake River Temperatures using the RBM10 Model—Draft. EPA Region 10, Seattle, Washington.
- Keefer, ML, Peery, CA and Caudill, CC, 2008. Migration Timing of Columbia River Spring Chinook Salmon: Effects of Temperature, River Discharge, and Ocean Environment. Transactions of the American Fisheries Society, 137(4): 1120–1133. <https://doi.org/10.1577/T07-008.1>.
- Mantua, N, Tohver, I, and Hamlet, A, 2010. Climate Change Impacts on Streamflow Extremes and Summertime Stream Temperature and Their Possible Consequences for Freshwater Salmon Habitat in Washington State. Climatic Change, 102 (1-2), 187. <https://doi.org/10.1007/s10584-010-9845-2>.

- McKenzie, SW and Laenen, A, 1998. Assembly and Data-Quality Review of Available Continuous Water Temperatures for the Main Stems of the Lower- and Mid-Columbia and Lower-Snake Rivers and Mouths of Major Contributing Tributaries. NPPC Contract C98-002. Northwest Power Planning Council, Portland, Oregon.
- Marcoe K, Collins C, Corbett C, Burke M, Schwartz M, Kolp P, and Hanson A, 2018. Lower Columbia River Thermal Refuge Study, 2015–2018. Lower Columbia Estuary Partnership, Hood River, Oregon.
- Niemeyer RJ, Cheng Y, Mao Y, Yearsley JR and Nijssen B, 2018. A Thermally Stratified Reservoir Module for Large-Scale Distributed Stream Temperature Models with Application in the Tennessee River Basin. *Water Resources Research*, 54, 8103–8119. <https://doi.org/10.1029/2018WR022615>.
- NorWest Stream Temperature Database, 2018. <https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html>.
- PNNL, 2017. Three-Dimensional Hydrodynamic and Water Quality Modeling of the Lower Snake River and McNary Pool. Pacific Northwest National Laboratory. <https://hydrology.pnnl.gov/projects/rmcnarypool.asp>.
- PSU, 2018. CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 4.1–User Manual. Department of Civil and Environmental Engineering, Portland State University, Portland, Oregon. <http://www.ce.pdx.edu/w2>.
- Simenstad, CA, Jay, DA and Sherwood, CR, 1992. Impacts of Watershed Management on Land-Margin Ecosystems: The Columbia River Estuary. IN: Naiman, RJ (ed.), Watershed Management: Balancing Sustainability and Environmental Change. Springer-Verlag.
- Vermeyen, TB, 2000. Review of Past Studies and Data Related to Temperature Management Options for the Columbia River below Grand Coulee Dam, Washington. USBR, Denver Colorado.

Minimum Instream Flows: An Empirical Study of Instream Flow Law and Policy

Adam Wicks-Arshack, Bradley Luff and Barbara Cosens

MINIMUM INSTREAM FLOWS WERE ESTABLISHED LATE IN THE PROCESS OF WATER ALLOCATION BY STATES IN THE PACIFIC NORTHWEST, AND THE CAPACITY TO ENFORCE THESE FLOWS MAY BECOME CRITICAL TO AQUATIC SPECIES AS CLIMATE CHANGE UNFOLDS. YET THIS CAPACITY IS LIMITED BY THE ABSENCE OF KEY DATA ON WHETHER MINIMUM FLOWS ARE MET UNDER CURRENT CONDITIONS. OUR OPEN ACCESS, INTERACTIVE TOOL WILL ALLOW USERS TO COMPARE MINIMUM INSTREAM FLOW REQUIREMENTS TO ACTUAL FLOW, EVALUATE GOVERNANCE APPROACHES, AND ASSESS THE RESILIENCE OF SUBBASINS TO A CHANGING FLOW REGIME IN THE PACIFIC NORTHWEST.

Throughout the Columbia River Basin, water resource departments are increasingly charged with the task of balancing an ever-growing demand on consumptive, out-of-stream, water uses with a competing mandate to preserve instream flows for environmental, recreational and aesthetic purposes. However, due to varying approaches to establishment of instream flows by state governments and a lack of readily available streamflow data, the efficacy of instream flow requirements is unknown. This lack of readily available information may hamper governmental capacity to modify instream flow laws to adapt to climate change impacts.

We have attempted to bridge these knowledge gaps, and support decisions by policy-makers, by creating a minimum instream flow database and interactive mapping tool that compiles streamflow monitoring data, and compares these flows to every designated minimum instream flow across the Pacific Northwest. In essence, we are creating a publicly available, quantitative tool for comparing minimum instream flow requirements to actual flow, evaluating governance approaches, and assessing the resilience of subbasins to a changing flow regime in the Pacific Northwest.

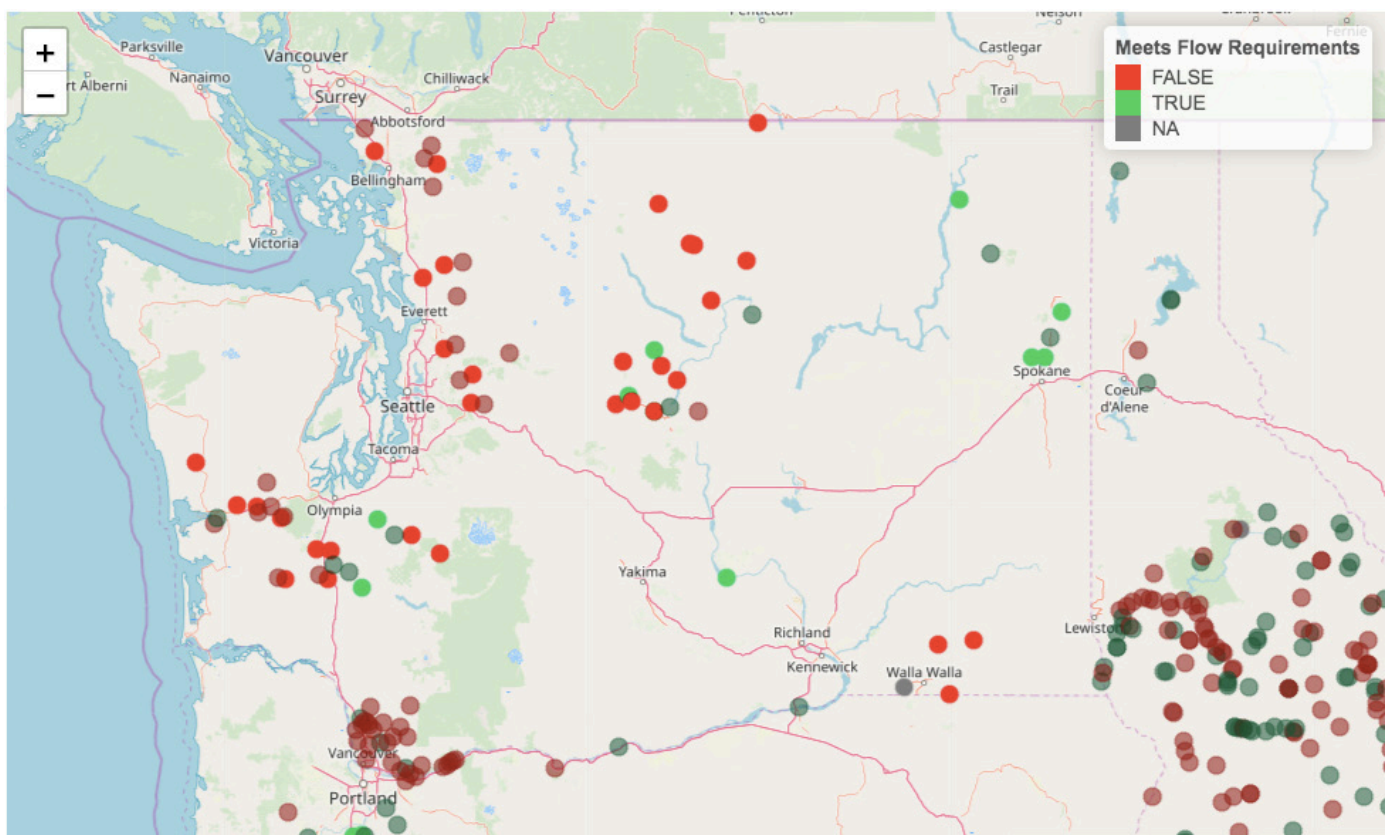


Figure 1. Screenshot of the interactive mapping tool, comparing flow data to the appropriate minimum instream flows designated for that location at that time of the year.

The premise of our tool is simple: real-time streamflow data are populated from state or U.S. Geological Survey streamflow gages, and located on an online map (Figure 1). This online map, which was created using the Shiny package in R, uses a simple color-coding scheme to indicate whether the measured streamflow is above or below the designated minimum flow. Minimum instream flows are determined using an array of science-based and non-science-based methodologies including baseflow and exceedance flows, instream flow incremental methodology (IFIM), and aesthetic or recreational needs. Where a minimum instream flow rule or water right does not reference a gage, daily outputs from the National Oceanic and Atmospheric Agency's National Water Model are used. However, due to the inherent inaccuracies of modeled streamflow data (especially at low flows and for smaller tributaries), we explicitly caution users if they plan to use the modeled data in monitoring or enforcement actions.

This tool can support both quantitative and qualitative legal analysis. For example, using the online mapping tool, one can select a stream reach or point of interest and determine whether that stream reach is meeting its designated minimum instream flow at that point in time. Or, using historical flow data, we can understand the frequency with which a stream reach does not meet the designated minimum instream flow; and we can identify stream reaches where expected long-term future changes in flows could lead to new—or exacerbate existing—instream flow violations, using historical and future predicted flow data. In sum, this presents a novel quantitative tool to help legal analyses evaluate governance approaches used by states and subbasins, and assess resilience to a changing flow regime in the face of climate change.

Water Storage and Economic Resilience in a Managed Hydrologic System

Moses Luri and Jonathan Yoder

WATER STORAGE IMPACTS A WATER SYSTEM'S ABILITY TO WITHSTAND EXTREME EVENTS AND CAN BE AN IMPORTANT DETERMINANT OF MANAGED HYDROLOGIC SYSTEM RESILIENCE. WE EXAMINE HOW WATER STORAGE MANAGEMENT CAN BE USED TO IMPROVE A MEASURE OF ECONOMIC RESILIENCE TO SUCH EXTREME EVENTS.

Water storage impacts a water system's ability to withstand extreme events and can be an important determinant of a managed hydrologic system's resilience. For example, reservoirs in a river system can help contain floods, or can store water until needed during droughts (Figure 1). Our area of interest is the economics of resilience. Specifically, our objective is to examine how water storage management may be used to improve a measure of economic resilience to hydrologic shocks, such as droughts and floods.



Figure 1. A storage dam on the Columbia River. Storage dams can help contain floods and can store water until needed.
Photo: Sonia A. Hall.

We combined economic theory with methods developed in ecology and water resource engineering to construct a model that reflects a simple managed water system with inflows that vary from year to year and a maximum storage capacity. We then use the model to:

- 1) Define and characterize resilience in this managed hydrologic system;
- 2) Identify key relationships between storage capacity, variations in water supply, and the system's resilience;
and
- 3) Calculate the economic value of system resilience for a specific model specification.

We started with an important question: what is storage used for? Suppose that storage decisions are made by a water reservoir or dam manager. Suppose further that the manager stores or releases water from the reservoir in any given period with the intent to maximize the expected value to users of existing water flows through the system, over the life of the dam and reservoir, given inter-period variations in inflows. Under these assumptions, the basic objective leads to a storage rule structurally similar to a well-known income saving and spending rule in economics: given expectations about future income (future inflows), people will tend to save and borrow (store or release water) when possible to smooth consumption over time (outflows for use). People tend to save when their income is high and draw down savings when income is low. In other words, storage is used to minimize the variation in outflows for consumption and use from one period to the next in order to smooth the expected availability and maintain similar

use of water from one period to the next. The dam manager will therefore tend to increase the amount of water held in the reservoir from high-water periods with lots of precipitation or a high snowpack, and draw down the water in the reservoir during droughts.

If storage capacity is huge compare to variation in inflows, the dam manager will be able to store and release water during high and low water years to allow for perfectly smooth outflows from the dam for use in each year. But if reservoir capacity is small compared to the variation in inflows, the dam manager will not be able to smooth outflows completely. For instance, if storage was low because of previous droughts, and another low-water period comes along, then outflows might be lower than normal. In contrast, a series of high-water periods may lead to a situation in which there is not enough storage to accommodate as much water for the future, so the dam manager has to let excess water spill over. In these cases, the value of water is not maximized, because insufficient storage constrains optimal water allocation and use across periods.

If one or more high-water or low-water years knock the dam manager off their objective, how long would it take for the dam manager to recover to the desired state of constant (or minimum-variance) outflows following a large inflow deviation? We defined resilience as the speed with which a system returns to normalcy (i.e. the preferred constant outflows level), following a single or multiple low-water years.

Preliminary simulations from our model showed that when storage capacity was big relative to inter-annual mean and variance of runoff, the dam manager could effectively leverage storage to provide smooth optimal outflows over time (Figure 2). More importantly, the impact of inflow shocks died off relatively quicker when storage was substantially large (Figure 3). We expect to be able to show that economic value associated with quicker returns (more resilience) is higher than with slower returns (less resilience).

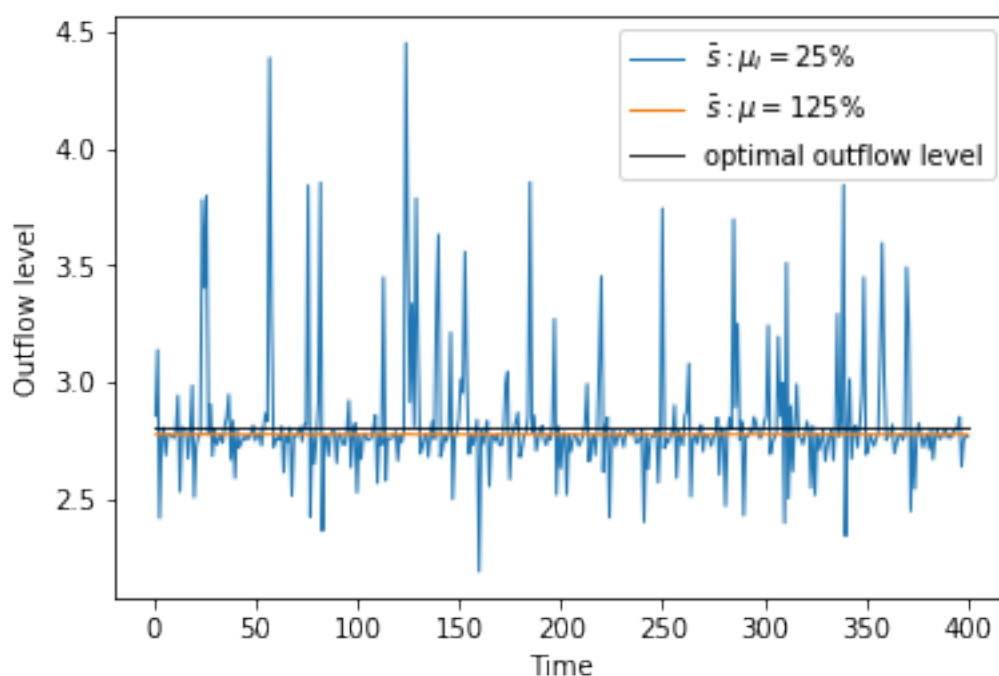


Figure 2. A comparison of variability in outflows for different storage capacity to average runoff ($s: \mu$) ratios. Variations in outflows was smaller where the storage capacity to average runoff ratio was 125% (orange line), compared to when the ratio was 25% (blue line).

Our initial results fall in line with some earlier reports from the Great Plains, Rocky Mountains and the arid Southwest: where water storage was up to 3.8 times the mean annual runoff, storage impacts on river discharge were significantly greater than other parts of the U.S., where storage was only 25% the mean annual runoff (Graf, 1999). Ultimately, the ability to achieve resilience in a water system through effective year-to-year storage management would depend on how large the storage capacity is relative to the within or between years' distribution of inflows in the system.

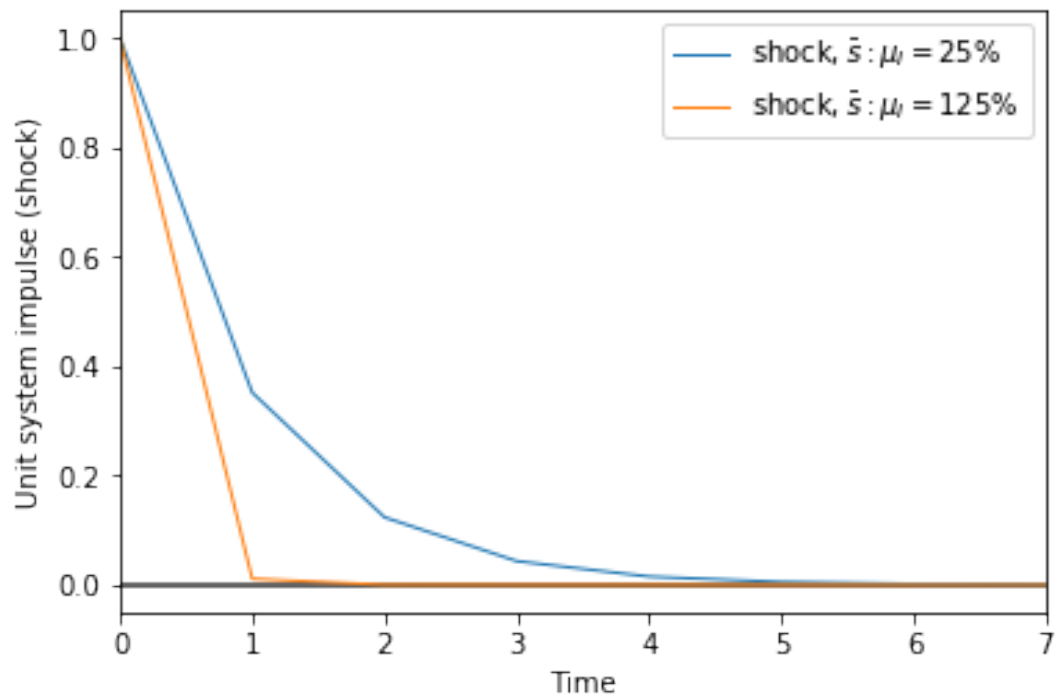


Figure 3. A comparison of system recovery speeds following a single shock of unit magnitude. The shock approached zero—that is, the system returned to where it was before the shock—faster when the storage capacity to average runoff ratio was 125% (orange line), compared to when the ratio was 25% (blue line).

References

Graf, W. L. (1999). Dam nation: A geographic census of american dams and their large-scale hydrologic impacts. *Water resources research*, 35(4):1305–1311.

3: How Are the Food, Energy and Water Sectors Expected to Change in the Future?

The Columbia River Forecast: What to Expect of the Columbia River's Water Supply and Demand

Sonia A. Hall, Jennifer C. Adam, Georgine G. Yorgey and Jonathan Yoder

THE 20-YEAR FORECAST OF FUTURE WATER SUPPLY AND DEMAND IN THE COLUMBIA RIVER BASIN SUGGESTS THAT SEASONAL SHIFTS IN BOTH SUPPLY AND DEMAND COULD LEAD TO POTENTIAL SHORTAGES BOTH IN EARLY SPRING AND LATE SUMMER. THESE PERIODIC FORECASTS CAN THEREFORE INFORM STRATEGIC INVESTMENTS IN WATER DEVELOPMENT AND POLICY DISCUSSIONS ON WATER USE FOR THE BENEFIT OF SOCIETY AND THE ENVIRONMENT. THE COLUMBIA RIVER BASIN LONG TERM WATER SUPPLY AND DEMAND FORECAST, THOUGH NOT PART OF THE COLUMBIA FEW PROJECT, IS INCLUDED IN THIS REPORT BECAUSE IT IS RELEVANT TO OUR UNDERSTANDING OF THE INTERCONNECTED FOOD-ENERGY-WATER SYSTEM IN THE COLUMBIA RIVER BASIN.

In the Pacific Northwest we have detailed data projections of future climate and its impacts within the region: warmer temperatures, especially at night, more rain and less snow, drier summers overall, earlier snowmelt and peak streamflows, more frequent large storms and rainfall events. Yet this information is not sufficient to help people and organizations in Washington State invest strategically in water development in the Columbia River Basin, for the future benefit of the society and the environment. Targeted 20-year forecasts (“the Forecast”) of future water supply and demand across eastern Washington are mandated by the Washington State Legislature, with updates required every five years. To accomplish this mandate, the Office of Columbia River within the Washington Department of Ecology has partnered with Washington State University, the State of Washington Water Research Center, and collaborators to complete the Forecasts for 2011 and 2016. Planning is currently underway for the 2021 Forecast.

At the core of the 2016 Forecast was an integrated biophysical model that allowed the Forecast team to quantify water supplies at the watershed level for instream and out-of-stream uses. This includes estimating how much water would be needed to support agricultural production (see description in Rushi et al.’s article), municipal water use, water for hydroelectric power production, and instream flow requirements within watersheds. By running the biophysical model with historical climate data (1981-2011), and rerunning the model with climate projections for the decade centered on 2035 (2020-2050), the Forecast quantifies how water supply and demand will likely change over the next 20 years.

The 2016 Forecast estimates that the water supply of the Columbia River at Bonneville Dam will increase by an average of 15% (plus or minus 8%) by 2035 (Figure 1). This increase includes a 31% increase in the spring counteracting a 10% decrease during the late irrigation season. The reasons for this change? Warming results in less precipitation falling as snow and more as rain, an earlier snowmelt leads to earlier peak streamflows, and springs are generally projected to become wetter.

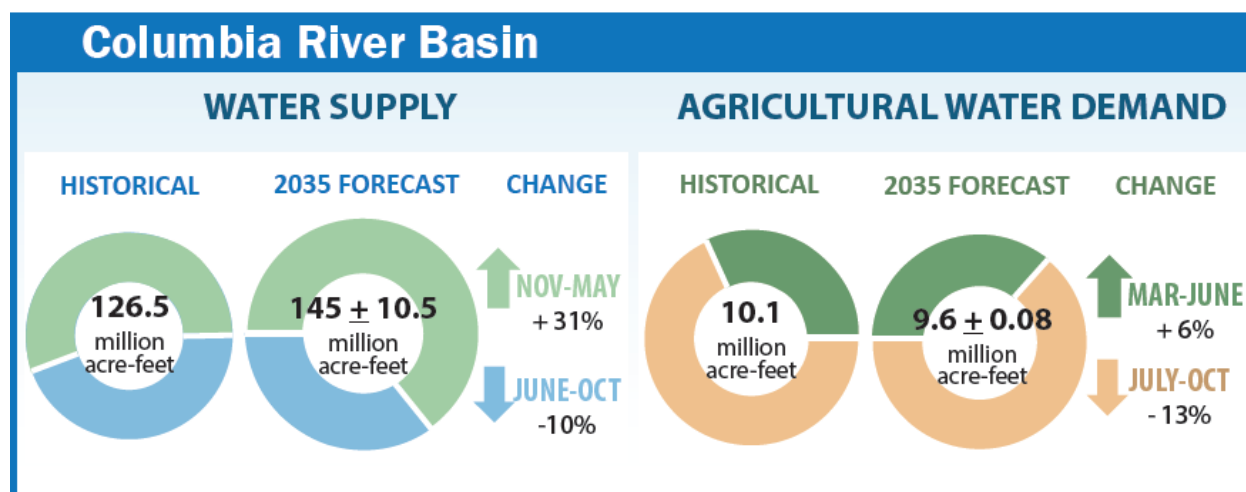


Figure 1. Historical and forecast (2035) water supply and agricultural water demand for the Columbia River Basin. These are results from the 2016 Long-Term Water Supply and Demand Forecast, reproduced from the associated outreach materials (<https://fortress.wa.gov/ecy/publications/SummaryPages/1612005.html>). Note that the agricultural water demand occurs from March through October, while the water supply is for the whole year, from November through October of the next year. Though water supply is significantly larger than demand across the whole Basin, timing of availability, difference among subbasins, and other demands for water—including instream needs—determine that shortages occur in the Columbia River Basin.

How will all these changes impact efforts to balance demands for water across different sectors? Water diverted for irrigated agriculture is the main out-of-stream water use in the region. Our integrated modeling suggested that, on average, agricultural water demand is expected to decrease 5% (plus or minus 1%) by 2035, and possibly more if the trend toward more water-efficient crops seen in the recent past accelerates (Figure 2). This decrease is the net effect of an increase in spring demand, and a decrease later in the season, on the same extent of irrigated cropland (Figure 1). These changes are partially due to warmer temperatures that would allow earlier planting of crops, accelerating their growth and leading to a shorter growing season.



Figure 2. Vineyards in Red Mountain, Washington. Washington is seeing increased acreage dedicated to water efficient crops like grapes. Photo: Washington State Department of Ecology, under CC BY-NC 2.0.

There are some important caveats to keep in mind. In addition to assuming that the amount of irrigated land remains unchanged, and that the current trend toward more water-efficient crops will continue through 2035, the model does not quantify what would happen as earlier and shorter crop cycles allow more farmers to plant longer-season varieties, double-crop their fields, or trade the conserved water. Back-of-the-envelope calculations suggest that an increase in double-cropped acreage could change this projected reduction in water demand to an increase in water needed by 2035. Better understanding the potential impact of double-cropping on agricultural water demand is a priority for the 2021 Forecast.

The Forecast results also indicate a trend toward less water security for some water-right holders in the spring, with a decrease in water interruptions later in the irrigation season at some locations and under some future climate scenarios (for example, Figure 3). The vulnerability of agricultural production to future changes in climate will be most apparent in drought years, which are expected to become more frequent and severe as warming continues.

The 2016 Forecast results focus on surface water only. However, water availability and use of groundwater is often connected. For example, groundwater in the Odessa Subbasin is used to irrigate agricultural lands in four counties. Groundwater provides a critical emergency response resource during drought in many areas. A focused review of declining groundwater in select areas in the 2016 Forecast documented widespread water-level declines and a reduction in stream baseflows. In addition, the [Whatcom County vs. Hirst et al. decision](#) has placed new requirements on future private domestic water development to limit the impact that new permit-exempt wells might have on surface water supplies (though those requirements have since changed; see [SB 6091](#)). Efforts to integrate groundwater into the Forecast will therefore continue through 2021.

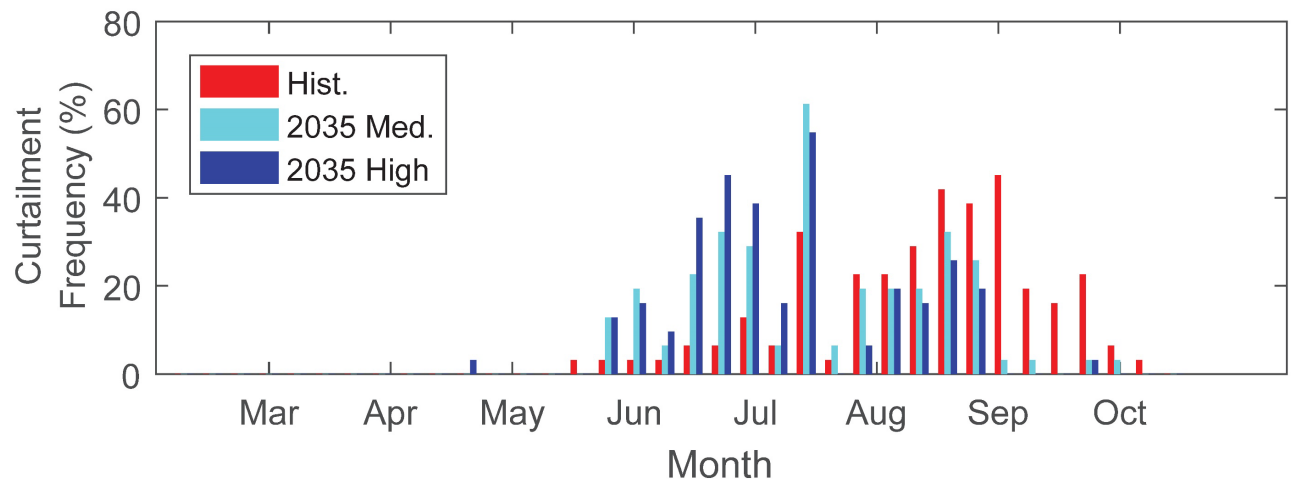


Figure 3. Modeled historical (1981-2011) and forecast (2035) median curtailment frequency (percentage of years that observe any amount of curtailment for a particular week) in the Wenatchee River. Curtailment is forecasted using the climate change scenario that projects changes in temperature and precipitation closest to the middle of all 5 climate change scenarios considered under each emissions scenario: the “2035 Med” and the “2035 High” values represent supply forecast under IPCC Representative Concentration Pathways (RCP) 4.5 and 8.5, respectively.

Other priorities for the 2021 Forecast are to quantify the impact of changing patterns in interruption of water to water right-holders, and to refine calculations of future municipal water demands, given the importance of this growing sector in the region. These improvements will help strengthen the information provided to the Office of Columbia River and the Washington State Legislature on water supply and demand by the 2040s, informing strategic investments in water development, and providing critical information for any policy discussions around water use and management in the Columbia River Basin.

The Columbia River Forecast is funded by the Washington State Department of Ecology’s Office of Columbia River. The 2016 Forecast includes many more and more detailed results than those summarized in this article. Please visit <https://fortress.wa.gov/ecy/publications/SummaryPages/1612005.html> for a highlight of results, visit <https://fortress.wa.gov/ecy/publications/SummaryPages/1612001.html> for the Legislative Report, and visit <https://fortress.wa.gov/ecy/publications/SummaryPages/1612008.html> for further technical details on how the 2016 Forecast was carried out.

Impact of Land-Use and Land-Cover Change on the Food, Energy, and Water Sectors in the Columbia River Basin

Matthew Yourek, Keyvan Malek, Mingliang Liu, Maoyi Huang, Claudio O. Stöckle, Jan Boll and Jennifer C. Adam

WE ARE USING SPATIAL DOWNSCALING OF GLOBAL LAND-USE AND LAND-COVER CHANGE PROJECTIONS AND HYDROLOGIC MODEL SIMULATIONS TO EXPLORE THE RAMIFICATIONS OF GLOBAL SOCIO-ECONOMIC AND CLIMATIC CHANGES FOR THE FOOD, ENERGY AND WATER SECTORS AND THEIR INTERACTIONS IN THE COLUMBIA RIVER BASIN.

Global-scale changes—economic, sociological, climatological—have important ramifications for local communities. Land-use and land-cover (LULC) change, one such transformative process, alters the balance of food, energy and water resources within a basin. We are interested in understanding the future impact of LULC change in the Columbia River Basin. This requires first understanding how LULC is expected to change, and then exploring the impacts of these changes on the different sectors.

Future Changes in the Columbia River Basin

The Global Change Assessment Model (GCAM) simulates supply and demand of fuel and agro-forestry commodities at the national level under a set of standardized greenhouse gas emission scenarios known as representative concentration pathways (RCPs). In the model, markets in food and fuel determine LULC change. Biofuel is among the industries expected to benefit from low carbon emission policies (Figure 1). To be meaningful within the Columbia River Basin, the broad-scale changes in land use for biofuels and other crops must be disaggregated to a finer scale. Our goal is to apportion Basin-wide LULC change to individual grid cells based on the underlying variability in land and climate suitability for various types of land use through spatial downscaling.



Figure 1. Biofuel industries, including switchgrass production, are expected to benefit from low carbon emission policies. Photo: Dennis Pennington, under CC BY-NC-ND 2.0.

We have adopted an existing downscaling tool, Demeter, to map the GCAM LULC change predictions onto grid cells across the Columbia River Basin. Demeter works by disaggregating the LULC change values among grid cells, subject to user-defined constraints on the intensification or expansion of each land type. Suppose for instance that GCAM projects an increase in wheat production. Demeter first searches for all grid cells containing wheat and tries to match the target increase in wheat area by increasing the proportion of wheat in those cells (intensification). The remaining target increase in area is apportioned among surrounding grid cells where wheat is not currently grown, based on their suitability for wheat (expansion).

Some land-use changes are constrained by regionally relevant factors, so we modified Demeter to incorporate those. First, we added a constraint based on water rights. Irrigators must acquire a right to irrigate. Therefore, the places of use of all water rights constrain the expansion of irrigated agriculture. Our second constraint restricts cropland to land that is suitable for cultivation.

Exploring Impacts

With the downscaled projections of future land-use change in the Columbia River Basin, we modeled resultant changes in agricultural water demand and crop yield under each scenario using the coupled hydrology-cropping systems model, VIC-CropSyst, targeting two different research questions:

- What impact would a global carbon policy have on the production of biofuels?
- How much does water rights expansion impact irrigation demand?

To answer these questions, we evaluated two emission scenarios, RCP 4.5 (low emissions) and RCP 8.5 (high emissions), and three levels of expanded irrigation (existing, moderate expansion, and full expansion, where “existing” reflects current water rights extent, “full expansion” considers that all suitable land has a water right, and “moderate expansion” assumes new water rights supply half of the additional suitable land currently without a right).

Preliminary results suggest that a low-carbon future (RCP 4.5), achieved through aggressive global carbon policies, would lead to a large increase in acreage for biofuels by 2060 (from a baseline of zero in 2015 to 12,340 km² [3 million acres]). By comparison, our results indicate that a high-emissions future (RCP 8.5) would result in 3,250 km² (800,000 acres) planted to biofuel crops (Figure 2A). We expect biofuels expansion to occur primarily by converting marginal lands, currently covered by forest and grassland (Figure 2C and D). Nevertheless, GCAM does predict a decrease in food production acreage (Figure 2B), especially for fruits and vegetables.

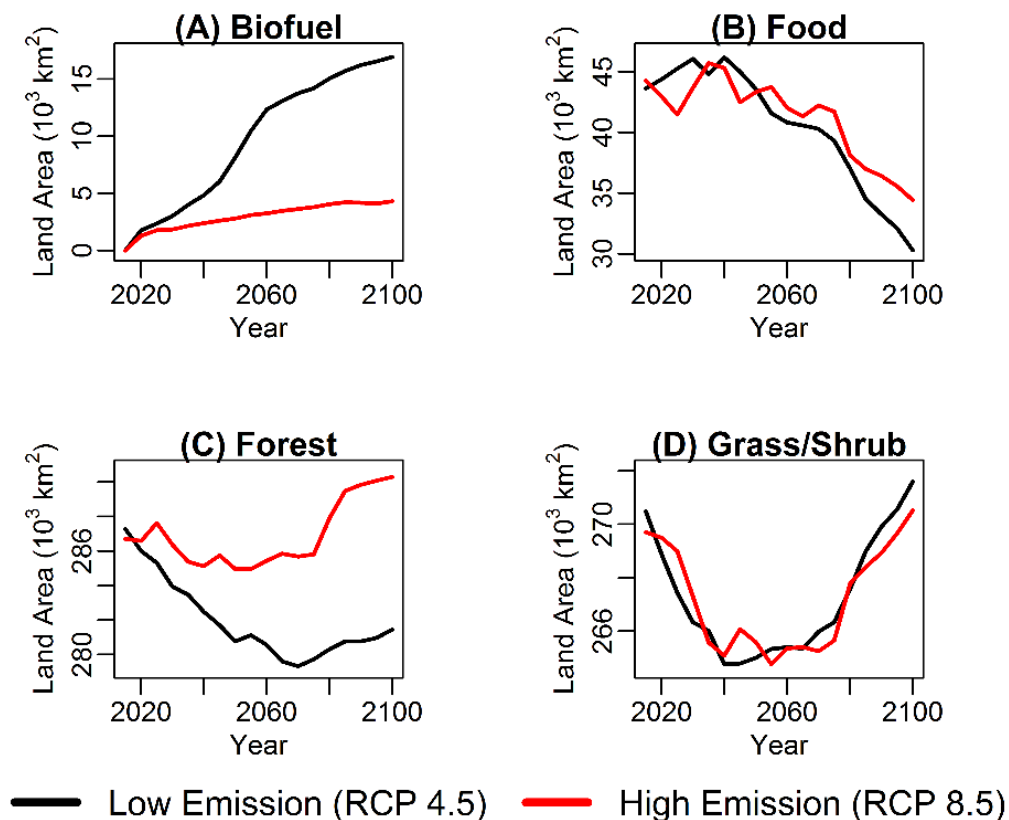


Figure 2. Trends in land use through the end of the 21st century in the Columbia River Basin, showing expected increases in area dedicated to biofuel production (A), decreases in area for food production (B), and changes in forested (C) and grassland/shrubland (D) area.

Assuming no changes to water rights, land-use projections suggest there will be about 40,000 km² (almost 10 million acres) of irrigated cropland in 2060. A full issuance of water rights to cover all suitable cropland would result in an increase to 66,800 km² (16.5 million acres). Under moderate expansion the irrigated area would increase to around 60,000 km² (see predicted distribution of irrigated area in 2060 in Figure 3).

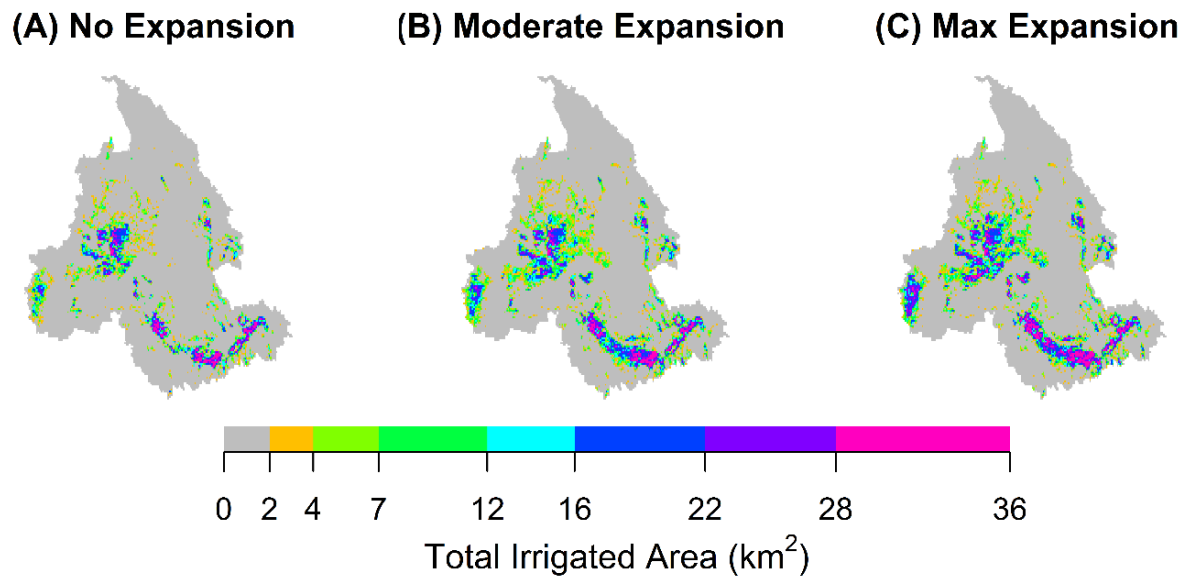


Figure 3. Projection of total irrigated area in the Columbia River Basin in 2060, when irrigated agricultural lands are constrained to suitable cropland currently with a water right (A), allowed to expand into 50% of suitable cropland currently without a water right (B), or to 100% of suitable cropland (C).

The reality of global trade in food and fuels means that land-use changes in the Columbia River Basin will be influenced by overseas markets. Water regulators and land-use planners should be mindful of such factors—both inside and outside the Basin—that lead to LULC change, such as our modeling captures. But questions remain. In the next phase we aim to quantify the energy production from biofuels compared to that from hydropower and to calculate the total irrigation demand under each water right expansion and RCP scenario. The irrigation demand will be compared with water supply to determine curtailment rates within selected watersheds to give a rough assessment of the feasibility of each expansion scenario.

Will Washington State Supplement Some of California's Expected Losses in Vegetable Production?

Fidel Maureira, Claudio O. Stöckle, Kirti Rajagopalan and Mengqi Zhao

CLIMATE CHANGE IMPACTS IN CALIFORNIA COULD POSE AN OPPORTUNITY FOR INCREASED VEGETABLE PRODUCTION IN WASHINGTON STATE. OUR WORK EXPLORES THE IMPLICATIONS OF SUCH AN INCREASE FOR THE FOOD, ENERGY AND WATER SECTORS IN THE COLUMBIA RIVER BASIN.

Climate variability and change—rising temperatures, more frequent heat waves, drought, less snowpack, pests and diseases, wildfires, and the resulting over-use of resources such as groundwater—are creating critical agricultural production risks for California, the leading vegetable and fruit producing area of the United States. These issues are projected to get worse in the future. In contrast, climate change-related challenges in the Columbia River Basin are projected to be less extreme and there is potential for a more favorable climate for certain agricultural products, providing the Columbia River Basin with relative competitive advantages over California. Can the irrigated areas of Washington State supplement some of the expected losses in vegetable production in California? The answer is not clear yet, but we can explore the implications of increasing vegetable production in the Basin, using climate change projections and models that quantify how regional hydrology and crops would respond to those climatic changes (Figure 1).

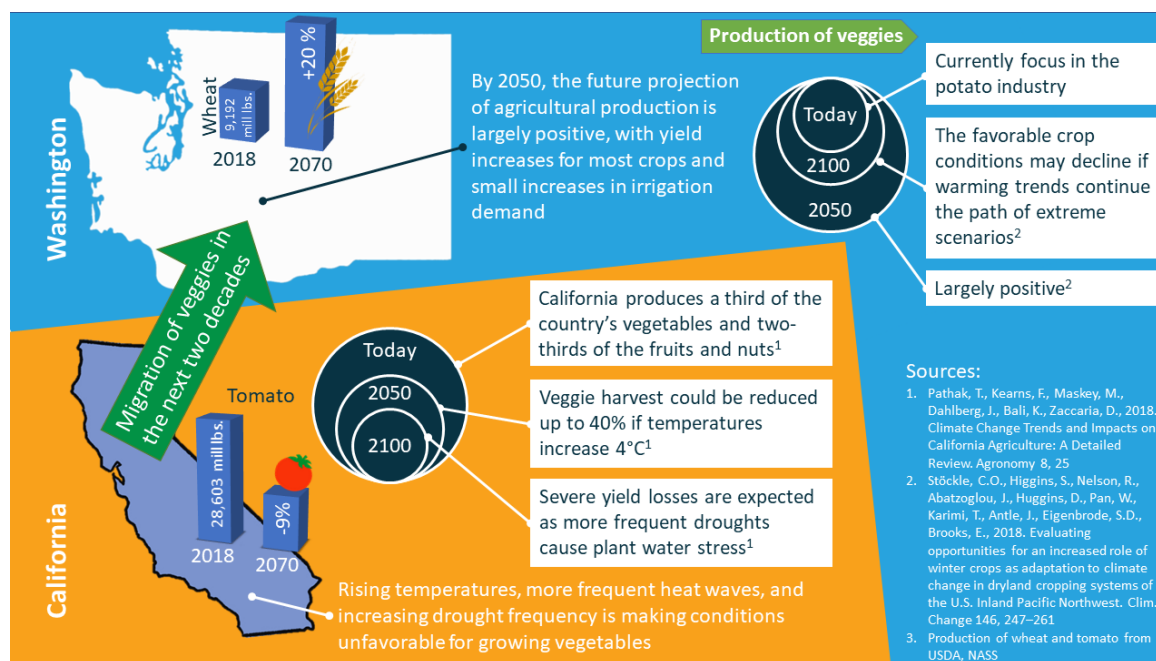


Figure 1. Vegetable production in California will suffer a reduction in total production because of rising temperatures effects on vegetables and a higher risk of water shortages. In contrast, Washington will show positive conditions in mid-century for growing crops and good supply of water. Can the irrigated areas of Washington State supplement some of the expected losses in vegetable production in California? This could be a beginning of new vegetable production in irrigated areas of Washington.

Although vegetable crops such as potatoes, sweet corn, onions and green beans are important crops in the Columbia River Basin, there is potential to consider new crops as well. In fact, there is evidence of past production of crops that are not currently prevalent; for example, tomatoes in the early 1900s (Figure 2). Additionally, some growers are currently taking the initiative of growing new vegetable crops in response to retailers looking for local sources. Currently, 7% of the vegetables offered by Walmart are locally produced. An example is the Imperial's Garden, owned by a family business located in the Yakima Valley, that produces more than 1,300 acres (526 ha) of asparagus, sweet corn, peppers, melon and tomatoes, among many other vegetables. They sell to groceries all around the Pacific Northwest.



Figure 2. Tomato production between apple rows in the Yakima Valley. Photo made digitally available by the Sloan Foundation, from Favor (1911), with no known copyright restrictions.

But why should we invest effort in understanding what an expansion of vegetable production in Washington State would mean? Because such changes in agricultural production could increase the water demand for crops and, where curtailments already point to limited water resources, an extra demand of water can build up to restrictions for other uses, such as energy generation, navigation, or wildlife.

To understand the implications of a vegetable production expansion, we will evaluate the feasibility of introducing new, open-field vegetable crops in the irrigated areas of Washington State. The production of open-field vegetables was considered, as it would keep most of the investments that growers have already made to produce existing crops, like central pivot systems and tractors. In a parallel article (see Maureira et al.'s greenhouses article) we will evaluate the implications on water and energy of producing tomatoes under greenhouse conditions. Using an agricultural land-use and CropSyst model, we will evaluate the implications of changes in cropland use, considering both biophysical and socio-economic drivers of change, such as increasing demands for food by 2050, and more suitable weather conditions in the region relative to other, out-of-state producers. CropSyst is a crop model developed in WSU during the last 25 years with the ability to predict the biomass and yield given the weather, soil and crop management conditions. Our proposed steps (Figure 3) include:

- 1) Simulating the growth, yield, water use, and nitrogen losses of existing crops and proposed new vegetable crops under current and future climate scenarios;
- 2) Determining the enterprise production budget for each crop, that estimates the costs and revenues associated with each of the cases simulated in step (1);
- 3) Estimating the trade-offs between the economic benefits to growers, obtained from step (2), and the environmental impacts, such as greenhouse gas emissions and water use, obtained from step (1);
- 4) Estimating the optimal change in crop types, considering the trade-offs in step (3) and adding a critical production area constraint: the minimum production of a given vegetable crop needed to justify the establishment of processing plant facilities; and
- 5) Evaluating the impacts and feedbacks of land-cover change on developing water storage management strategies with our team's system dynamics model of the food-energy-water (FEW) system (see Zhao and Boll's article).

Now is the time to better understand how the expansion of vegetable production in Washington State could affect the reliability of water available for irrigation, or the impacts on agricultural water demand and how that might affect competing uses of water (for example for energy generation), and what environmental impacts the new crop production might have. We can also better understand whether innovative storage management, such as managed aquifer recharge, could affect the trade-offs between FEW sectors. By doing so, we hope to provide decision-makers across the food, energy and water sectors with better information as they determine if, when, and how to manage for or around future changes in vegetable production in Washington State.

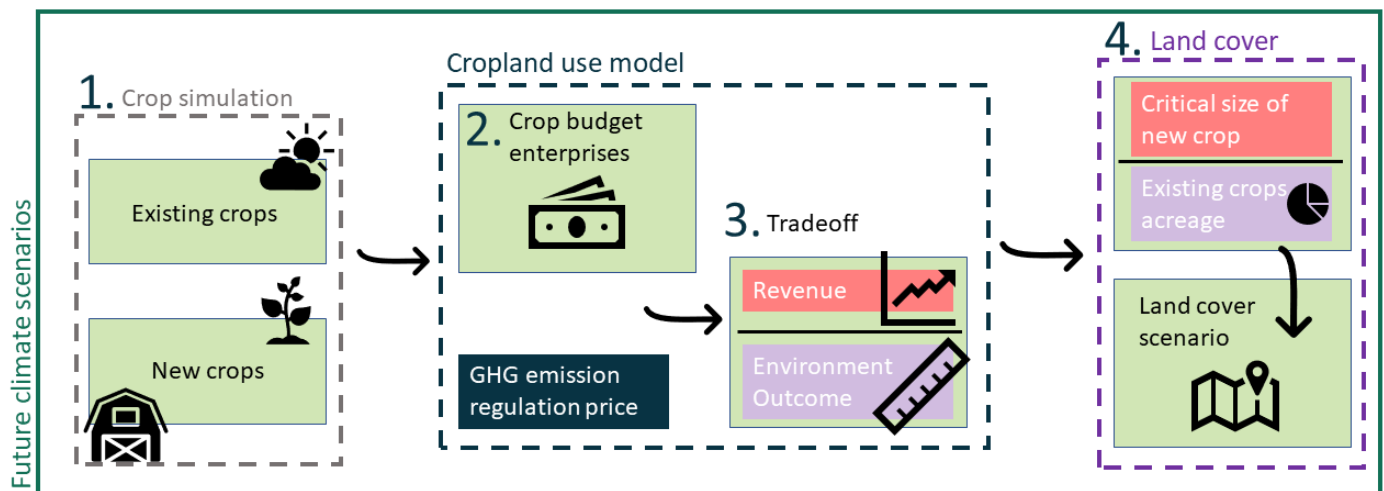


Figure 3. Steps to evaluate the implications in the Basin of changes in cropland use, considering the biophysical and socio-economic conditions of Washington State.

References

Favor, E.H. 1911. The Fruit-Growers Guide-Book. The Fruit Grower. St. Louis, MO. 285 pp.

Are Efficient Irrigation Technologies a Winning Solution in the Yakima River Basin?

Keyvan Malek and Jennifer C. Adam

IMPROVING THE EFFICIENCY OF IRRIGATION SYSTEMS HAS IMPLICATIONS FOR BASIN-WIDE AGRICULTURAL WATER AVAILABILITY, ENERGY SUPPLY AND DEMAND, AND THE ECOLOGY OF THE RIVER SYSTEM. OUR RESULTS SUGGEST THAT CLIMATE CHANGE CAN EXACERBATE SOME OF THE NEGATIVE IMPACTS OF THESE IMPROVEMENTS. WE ARGUE THAT WATER RIGHTS AND INFRASTRUCTURE CONTROL THE OVERALL CONSEQUENCES OF IMPROVEMENTS IN IRRIGATION TECHNOLOGY, HIGHLIGHTING THE IMPORTANCE OF REGION-SPECIFIC STUDIES.

Agro-hydrologists—people who study the dynamics of water in agricultural systems—have frequently pointed out that one farmer’s investment in new, irrigation efficiency technology improves the productivity of investing farmers, while it can negatively affect other farmers and water-use sectors (see, for example, Grafton et al. 2018). However, questions remain, as past studies have not explicitly quantified the impacts of new irrigation systems on other sectors. What are the implications for basin-wide agricultural productivity? How do efficient systems impact the ecological condition of the basin? How do energy production and demand change as people switch to more efficient systems? Are there any social implications? And do these productivity, ecological, and social implications change as the climate changes?

In the real world, climate change and improvements in irrigation technology happen simultaneously, but most studies do not evaluate their compound impacts. Moreover, most of the modeling frameworks used in other studies tend to simplify significantly the complicated nature of interactions between agricultural and physical processes, water rights, and the operation of dams and other water infrastructure. We used coupled physically-based modeling frameworks that mechanistically capture key water, agricultural, and human decision-making processes to quantify the impacts of investing in efficient irrigation technology on different aspects of the connected food-energy-water (FEW) system in the Yakima River Basin.

We considered eleven different climate scenarios: one historical (1980-2010) and ten future scenarios (2030-2090). Three irrigation efficiency investment scenarios include a “no action” scenario, which maintains existing technologies, an “all switched” scenario, which assumes efficient irrigation systems are universally employed, and a “market-driven” scenario, where efficient technologies are deployed according to individual farmers’ cost-benefit analyses (for details on the cost-benefit analyses see Malek et al. 2018). This scenario assumed that farmers would switch to a more efficient system if the calculated benefits were greater than the costs. By evaluating individual cost-benefit analyses cell by cell, we created a map representing this third investment scenario. The “market-driven” scenario describes a moderate trend towards expansion of drip irrigation and center pivot systems in the Yakima River Basin.

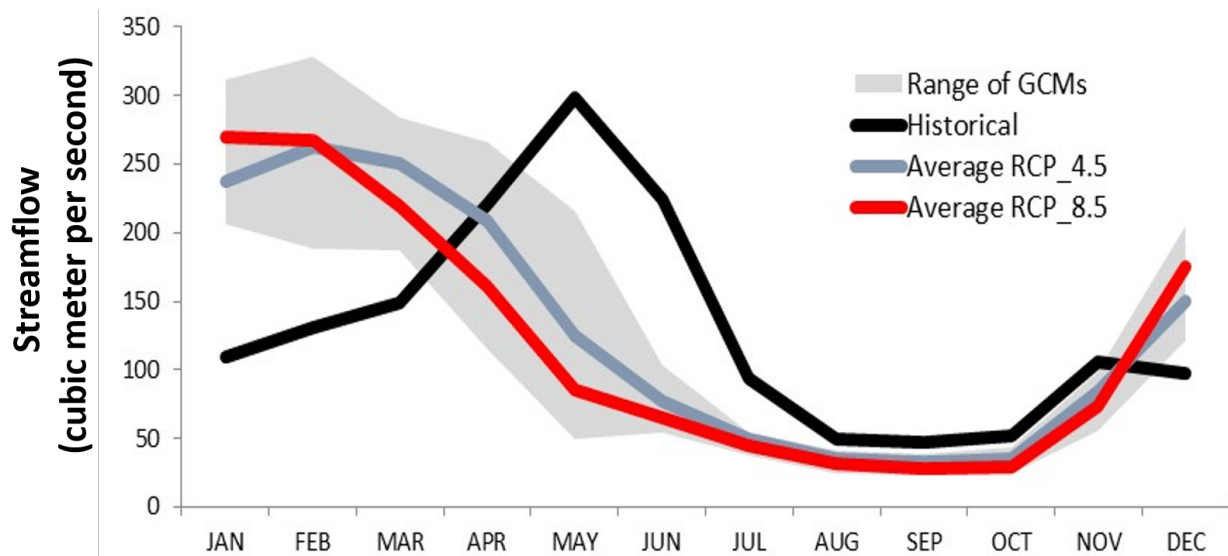


Figure 1. Changes in average streamflow under a changing climate. Note that RCP stands for Representative Concentration Pathways, which basically indicate different levels of atmospheric CO₂. RCP_8.5 shows a stronger change in climate.

Major findings

When we looked at a variety of metrics of agricultural productivity, ecological processes, and socio-economic factors across the three irrigation efficiency scenarios, and under historical and projected future climates, we found that:

- 1) More efficient irrigation increases consumptive use and evaporative loss, and reduces return flows. The U.S. Bureau of Reclamation estimates that return flows constitute 40% of the Yakima Basin's total water supply during the summer.
- 2) Irrigation demand declines, reducing the diversions for irrigation and offsetting some of the negative consequences of a reductions in return flows.
- 3) Although efficient irrigation systems lead to profits for investing farmers, overall impacts of new irrigation systems for other farmers and water-dependent sectors is negative.
- 4) The effects of climate change on streamflow is stronger than that of new irrigation technologies. Streamflow increases during the spring, and decreases during the summer (Figure 1).
- 5) Hydropower generation declines in the Yakima Basin, as a result of the changing streamflow profile.
- 6) Basin-wide energy demand in the agricultural sector falls due to lower water demand and expansion of energy-efficient systems (e.g., LEPA and drip irrigation).
- 7) Positive and negative consequences are not proportionally shared among all stakeholders. Our analysis of efficient irrigation systems found that the economics of the agricultural sector improve (Figure 2), while there are adverse effects for fishing and hydropower generation. Also, the number of workers employed in the agriculture sector declines, which might have social consequences as well. Therefore, we expect there will be winners and losers, which further socio-economic analyses should explore.

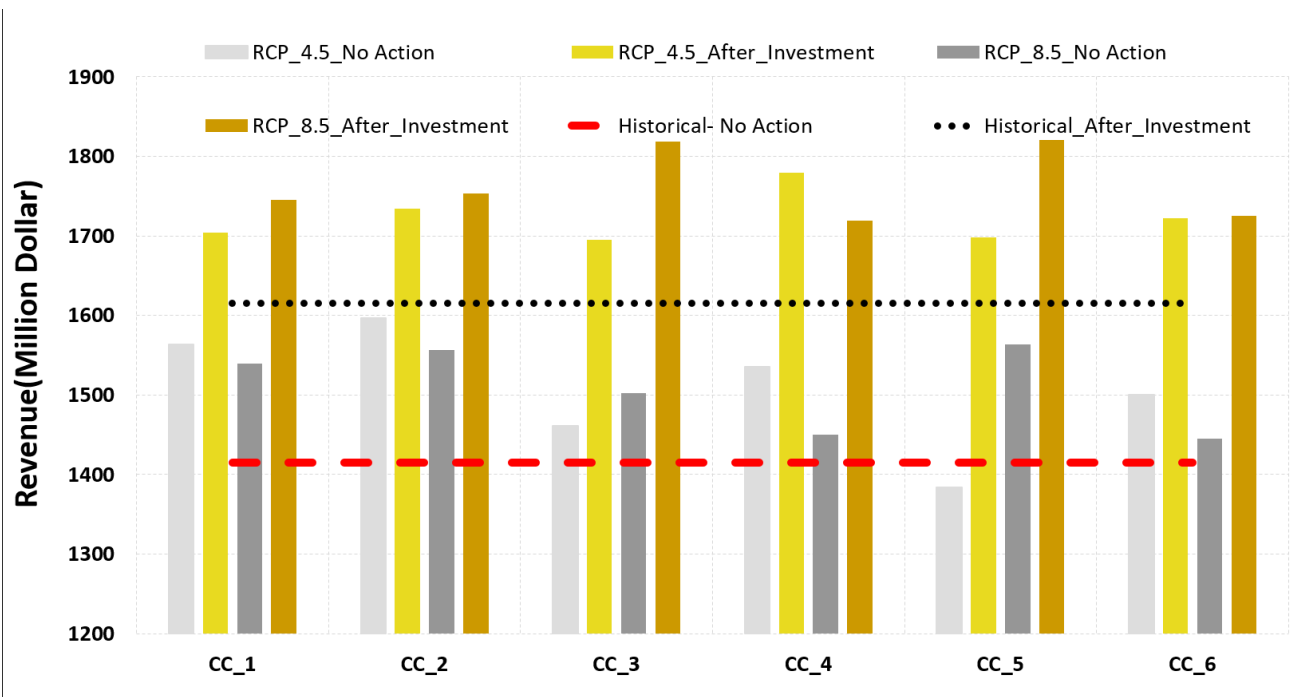


Figure 2. Improved economics of the agricultural sector with investment in more efficient irrigation technology. CC stands for climatic condition, and CC_1 to CC_6 are consistent with climatic condition in 2020s to 2080s decades.

Concluding Remarks

It is almost impossible to generalize our findings, simply because they are controlled by factors, such as the structure of water rights and reservoir systems, that are only applicable to the Yakima River Basin. If a decision-maker in a different basin wants to know what would happen if they supported a farm-level water conservation initiative, they would need basin-specific studies that consider all the key conditions within that basin. Our modeling framework, however, is transferrable, so can be adopted for those basin-specific conditions.

Although we are confident that this study is a significant step towards a better understanding of interactions between agricultural systems, water resources, and other water-dependent sectors in the Yakima River Basin, there are other scenarios that should be explored. Next steps include considering changes in water regulations in the Yakima River Basin, whose results could help evaluate potential alternatives as climate change leads to important change in the region's hydrology, impacting the food-energy-water system in the region.

References

- Grafton, R. Q., John Williams, C. J. Perry, Francois Molle, Claudia Ringler, Pasquale Steduto, Brad Udall et al. "The paradox of irrigation efficiency." *Science* 361, no. 6404 (2018): 748-750.
- Malek, Keyvan, Jennifer Adam, Claudio Stockle, Michael Brady, and Kirti Rajagopalan. "When Should Irrigators Invest in More Water-Efficient Technologies as an Adaptation to Climate Change?." *Water Resources Research* 54, no. 11 (2018): 8999-9032.

Adaptation to Climate Change in Agriculture: What are the Trade-Offs?

Kirti Rajagopalan, Keyvan Malek, Jennifer C. Adam, Claudio O. Stöckle, Mingliang Liu, Michael P. Brady

ADAPTATION TO CLIMATE CHANGE IN THE AGRICULTURAL SECTOR CAN LEAD TO SYNERGIES OR TRADE-OFFS ACROSS THE FOOD, ENERGY AND WATER SECTORS. HERE WE EXPLORE THESE SYNERGIES AND TRADE-OFFS WHEN DIFFERENT COMBINATIONS OF ADAPTATION STRATEGIES ARE ADOPTED ACROSS A WATERSHED. WE HOPE TO IDENTIFY WIN-WIN-WIN STRATEGIES THAT CAN ALLEVIATE FRICTION POINTS BETWEEN SECTORS.

Climate change-related temperature increases and changes in the frequency and magnitude of precipitation events are anticipated to affect crop production and water availability in the Pacific Northwest. These effects can and should drive adaptation in the agricultural production sector, that in turn could affect other related sectors such as energy production and the provision of instream flows for fish. For example, warming and increased growing-season length could lead to adoption of slower growing crop varieties, as well as increases in double-cropping. Economic factors and changes in expectations of drought frequency and severity could lead to adoption of new technology (such as irrigation technology) or different crop choices (see Maureira et al.'s vegetable production article). Adaptation can include long-run choices, often requiring an initial investment, and short-run choices, such as decisions in a specific drought year (Figure 1).

Integrated Adaptation Scenarios

Drivers/Expectations

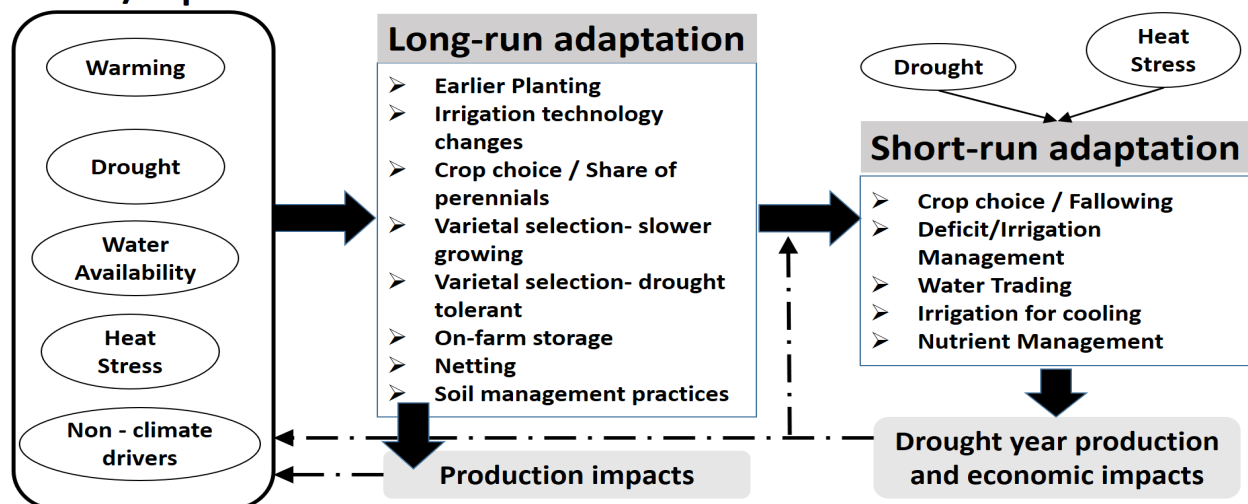


Figure 1. Adaptation to climate change and other drivers in the agricultural sector can be long-run or short-run.

Producers who adopt these strategies do so with a view of reducing risk at the farm level. However, this can result in synergies or unintended consequences across sectors at the aggregate system level, especially when multiple adaptation strategies are adopted in combination. Using the conceptual framework of food-energy-water relationships, we are working to characterize the synergies and trade-offs that exist across the food, energy and water sectors when different combinations of adaptation strategies are adopted across a watershed. Our focus will be the Yakima River Basin, because of its diverse crop mix, the significant amount of inefficient irrigation systems in use, and their exposure to water shortages.

We are exploring the use of flower diagrams (Figure 2) as a way to emphasize the trade-offs that this study finds, as we explore the adoption of adaptation strategies across the Yakima River Basin. By representing the value of key variables for the food, energy, and water sectors—such as food production, energy production, instream flow for fish—and how models project they will change through time, it will be easy to visualize when particular changes are positive (line moves from the zero hexagon outward) or negative (line moves from the zero hexagon inward) for each sector. Changes where the three lines move in the same direction (e.g. outward) show synergies, while changes where one or more lines move in the opposite direction to the rest show trade-offs.

As an illustrative example, climatic changes alone could have a negative effect on the food sector, as higher temperatures accelerate crop growth, decreasing productivity and irrigation demands. This could lead to increases in energy production and instream flow for fish, however (Figure 2a). Producers could react in several ways to address these climate change impacts. One option is the use of slower maturing varieties of crops, which have greater irrigation needs. This could increase crop production, but at the cost of detrimental impacts to other sectors, as more water would be used in food production (Figure 2b). Another option would be to combine the slower maturing varieties with improvements in irrigation efficiencies, which can potentially improve yields by better redistribution of soil moisture. If the irrigation water savings are left in the stream, this can lead to positive outcomes for energy production and environmental flows as well (in spite of reductions in return flows, as discussed in Malek and Adam's article; Figure 2c). In the absence of policies and incentives that encourage leaving the water savings instream, however, producers could spread that water across more irrigated acreage, leading to negative consequences for the other sectors (Figure 2d).

As we calibrate models to represent the conditions and context of the Columbia River Basin and produce quantitative results that reflect what impacts we might expect in the future, information from the flower diagrams, representing synergies and trade-offs, can feed into the STAR Calculator envisioned as part of this project (see Richey et al.'s article), and will be of value in identifying win-win strategies across multiple sectors, as well as minimizing the possibility of unintended consequences.

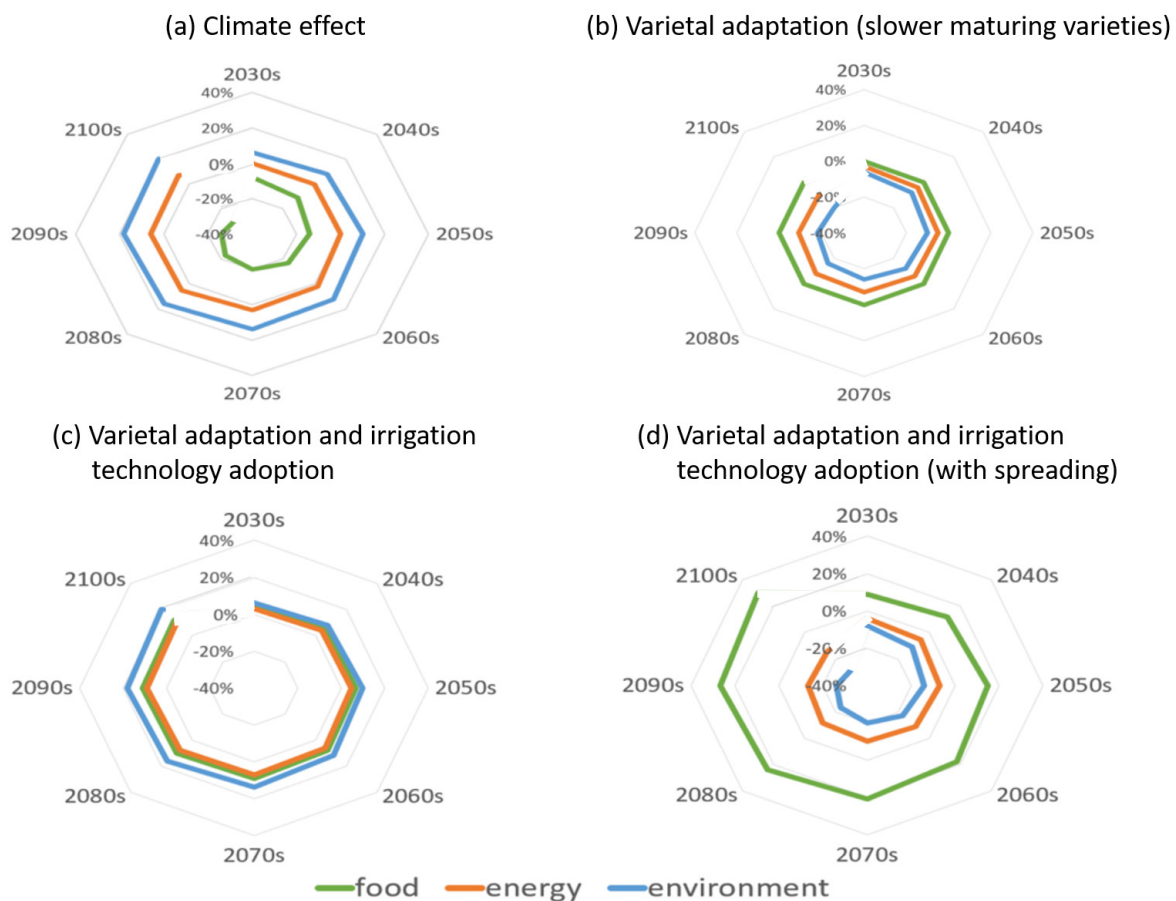


Figure 2. Example conceptual trade-offs and synergies. Each color represents a food-energy-water (FEW) sector, the points along the circumference of the flower diagram represent decades into the future, and the depth of the flower diagram represents levels of impact—positive or negative—to the sectors, as a percentage change.

4: Key Innovations That Could Resolve Friction Points Between Food, Energy and Water Now and in the Future

Greenhouse Production of Vegetables: Implications for the Regional Food-Energy-Water System

Fidel Maureira, Claudio O. Stöckle and Kirti Rajagopalan

GREENHOUSE AGRICULTURAL PRODUCTION IS A RAPIDLY GROWING INDUSTRY THAT LARGE RETAILERS ARE SHOWING SIGNIFICANT INTEREST IN. GIVEN THE POTENTIAL FOR HIGHER YIELDS, AND DIFFERENT WATER AND ENERGY REQUIREMENTS AS COMPARED TO TRADITIONAL PRODUCTION METHODS, WE EXPLORE THE IMPLICATIONS OF LARGE-SCALE ADOPTION OF THIS TECHNOLOGY FOR THE FOOD-WATER-ENERGY SYSTEM IN WASHINGTON STATE.

Greenhouse agricultural production currently accounts for 1 to 2% of the agricultural production in the United States, but is rapidly growing. The value of this greenhouse production has increased 44% in the last years, and the number of operators has gone up by 71%. Large retailers have a significant interest in this technology, given the benefits of consistency in quality, flavor, and production volume, the potential for year-round supply, consumer preferences for local supply, and the perception that greenhouse production can be more sustainable than traditional production, with more efficient use of resources. New, larger, commercial operations tend to be concentrated around bigger cities to satisfy those local needs. This trend is true in other parts of the world as well, including neighboring Canada.

Greenhouses provide a tightly controlled environment, where computer systems allow strict management of ventilation, lighting, irrigation, humidity, temperature, and carbon dioxide concentration, with higher yields and resource use efficiency. These factors are all energy intensive, and therefore energy requirements can be large. Most of the technology is imported from the Netherlands, where it has been fine tuned in the last few decades to help achieve their national goal of “producing twice as much food with half the resources.” Adoption of this technology has helped the Netherlands become a global leader in the export of tomatoes, potatoes, onions and other vegetables, in spite of a lack of access to a massive land area, considered necessary for large-scale agriculture.



Figure 1. Greenhouse production facility for bell peppers. Photo: Fidel Maureira.

While greenhouse production of vegetables is not currently prevalent in the Columbia River Basin, given the national and global trend, and given the fact that it has been successfully incorporated just across the border in Canada (Figure 1), we plan to explore the impacts of this innovation on the food-energy-water system in Washington State. To get a better sense of the technology, production practices, and challenges, part of our team visited a bell pepper greenhouse production facility in British Columbia in 2018 (Figure 2). We also invited American Ag Energy—a company based on the U.S. East Coast, that is focused on integrating greenhouse production with power plants—to visit our team and discuss their operations. For example, we learned that the technologies prevalent in British Columbia were developed for milder summers and might not apply directly to a hotter areas such as central Washington State. Another factor that came up was the importance of having clean rainwater available, with associated questions around the legal feasibility of rainwater collection in Washington State, and whether it would be permitted under current water laws.



Figure 2. Team visiting greenhouse production facilities in British Columbia, Canada. Photo: Mengqi Zhao.

We plan to use a system dynamics model for greenhouse production to explore the potential to produce more food without exacerbating existing friction points between the water and food sectors in Washington State. Greenhouse production may even have the potential to alleviate friction points due to higher resource use efficiencies, albeit their higher energy use. We will apply the model to:

- 1) Characterize the impacts of introducing greenhouse vegetable production on the food-energy-water system of Washington State,
- 2) Evaluate the potential to capitalize on opportunities unique to the region, such as access to 15 million acres of timberland and landfills for bioenergy production and carbon dioxide enrichment, and utilizing heat generated from data farms in the region,
- 3) Compare the production per unit land and water, as well as the environmental footprint, of greenhouse and open-field vegetable production, and
- 4) Obtain a list of the elements and conditions that will make the greenhouse feasible under future conditions expected in the region.

This work should inform the decisions of those in the food sector who are considering adopting this innovation, policy-makers considering incentives to produce more food with less resources, as well as planning agencies who need to be cognizant of the impacts of large-scale adoption of this innovation on the water and energy sectors.

EAGERS: The Tool Behind the Energy Optimizations

Ashley Mills and Dustin McLarty

THE EVER-CHANGING ENERGY SECTOR CONTINUES TO SEE INCREASES IN THE DEMAND FOR POWER AND A TRANSITION TOWARDS SOLAR AND WIND RENEWABLES. IN ORDER TO USE OUR EXISTING RESOURCES AS EFFECTIVELY AS POSSIBLE, WE DEVELOPED A NEW METHOD TO OPTIMIZE EXISTING AND NEW POWER INFRASTRUCTURE UNDER VARIOUS FUTURE CLIMATE AND DEMAND SCENARIOS WHILE CONSIDERING THE CONSTRAINTS OF THE DIVERSE ENERGY SOURCES.

The Columbia River system plays a central role in energy production and irrigated agriculture, as well as meeting instream flow requirements. Management decisions in the future will be complicated by changing water availability, increasing irrigation and energy demands, and changing energy sources. We are using a newly developed optimization framework, “Efficient Allocation of Grid Energy Resources including Storage” (EAGERS), to better understand the implications of such changes. The EAGERS tool determines an optimal, system-wide dispatch of water and energy resources to meet power demands, instream flows for flood control and the needs of fish species, and agricultural irrigation demand.

To run the EAGERS optimization the user must provide information about the network they are studying, using four pre-designed spreadsheets. These inputs include information about energy and water demands, the energy network, stream flow, and the components of the energy network, which are outlined below.

Energy and Water Demand

The demand data reflect what your network is being optimized for. For example, you may want to provide the total electric load (or electric demand) to power a community that has grown in population, with cost being the main concern in optimizing. You can then use historical data, or create a scenario that you would like to explore, as inputs for the energy demand. If your scenario contains a hydroelectric component and you wanted to analyze the impact of additional water needs, you could add a water demand relevant to your desired scenario.

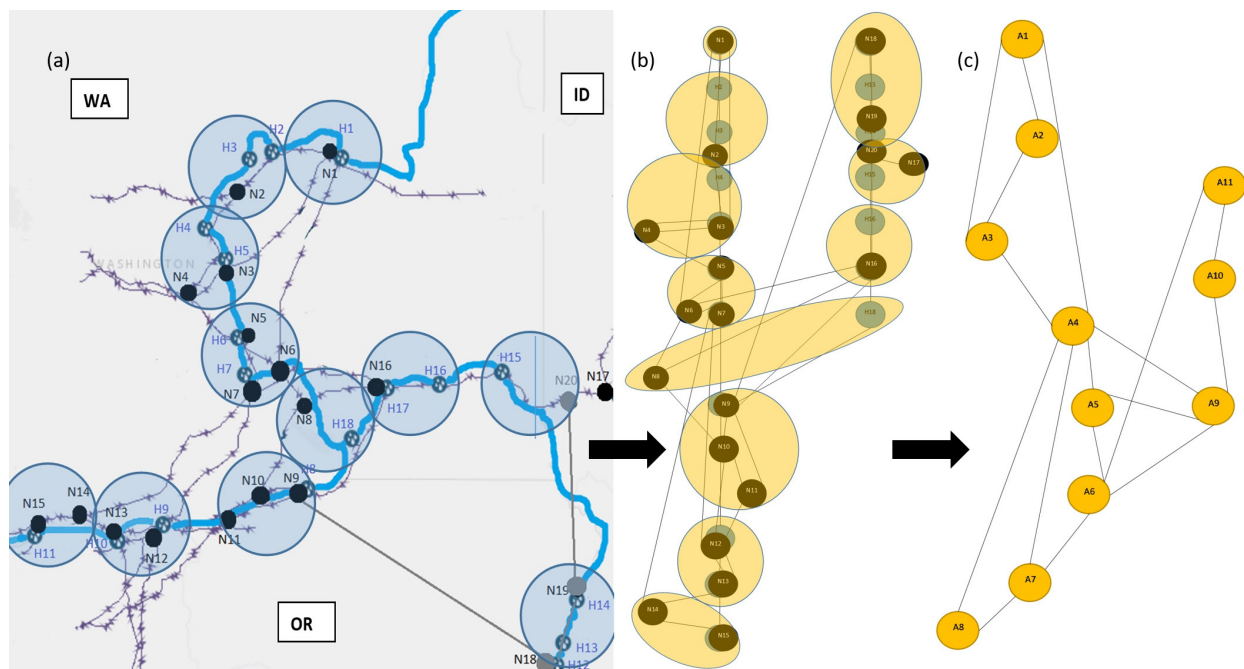


Figure 1. (a) Hydroelectric plants (small grey circles), electric power plants (small black circles), river sections (blue lines), and electric power lines (black lines) in the Washington portion of the Columbia River Basin. Large blue circles are analogous to the yellow ovals in panel (b). (b) Representation of the energy network in Washington as a set of nodes (brown circles) and connections (straight lines). Nodes where there is near-perfect transmission of energy are aggregated (yellow ovals), while those where transmission of energy incurs losses are kept as their original nodes with no aggregation. (c) Final simplified representation of the aggregated nodal network.

Energy Network

The network information includes the locations where energy is obtained from the river and where it is used, the connections that exist between those locations (river sections and electric power lines), and the losses associated with transferring energy through those connections (estimated as transmission factors). This information is then used to create the aggregated network, which is a simple set of nodes and links, where each node aggregates locations whose connections have perfect or near-perfect transmission factors (Figure 1). For example, river systems that have some form of water loss when traveling downstream between reservoirs, which translates into imperfect transmission factors, will be represented by nodes along the river system that are not aggregated.

Stream Flow

This includes values for all inflows and outflows associated with the reservoirs being optimized (Figure 2). In addition, we also need information on the loss (diversion) or gain (source) of water flow in the river segments between the reservoirs (Figure 2). For example, a tributary flowing into the river segment would be a source, while water being drawn out of the river segment for irrigation would be a diversion. These variables are used to prevent unrealistic optimization, ensuring that no water simply appears or vanishes. The flows are entered as a starting point to the optimization. After that, the model will quantify “optimal” flows, which will replace these inputs.

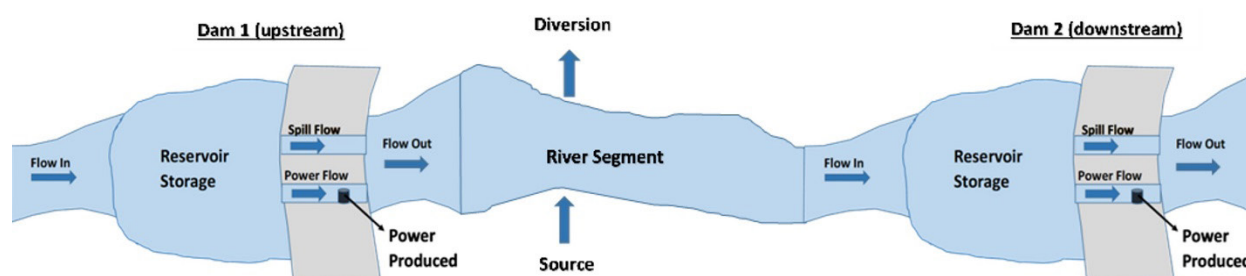


Figure 2. Aerial view of generic concrete dam and associated reservoir showing the terminology used in EAGERS for flow in, spill flow, power flow, flow out, reservoir storage, diversion flow (e.g. to irrigated agriculture) and source flow (e.g. from a tributary).

Network Components

Components may include fossil fuel plants, hydroelectric plants, solar and wind farms, utilities, or various other components that are important to find a realistic optimization. The user can include specific attributes, such as size or power generation capabilities, for each of the components represented.

A significant challenge with optimizing systems with hydroelectric reservoirs is that short-term (e.g., weekly) optimizations could deplete or overfill a reservoir, making it impossible to effectively address the need for a large drawdown in the dry summer months, or the need for excess space for flood control later in the year. EAGERS addresses this challenge by creating a forecast for the water year (October 1 through September 30), with an upper and lower bound to allow for some variability (Figure 3). These boundary conditions drive the optimization to hold to the forecast whenever possible. Although it does not stop the optimization from choosing values outside of these boundaries, it applies an increasing cost penalty when it does so.

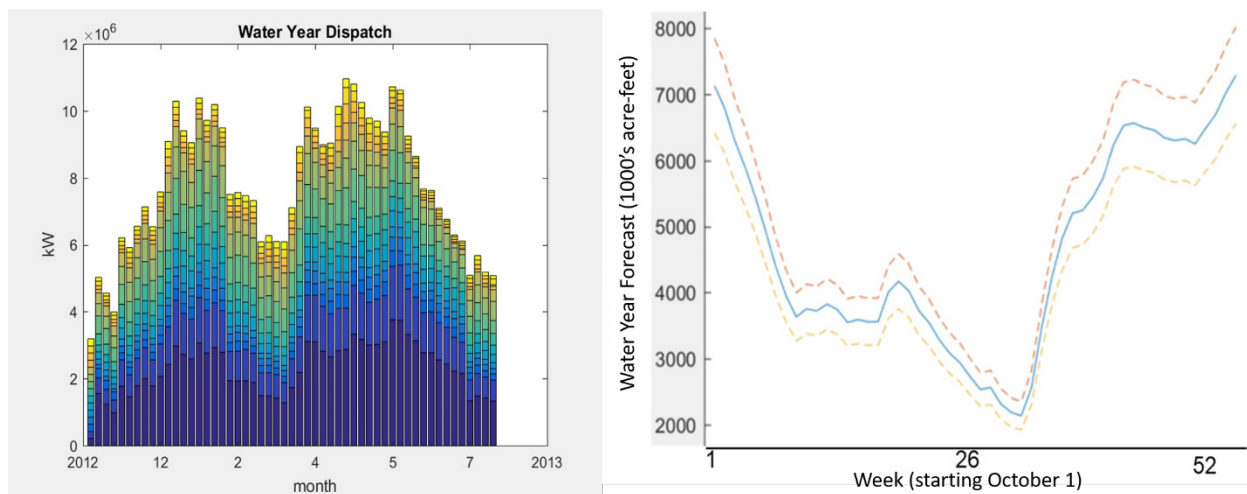


Figure 3. (Left Panel) Example forecast for a water year from October 1st 2012 through September 30th 2013 at a weekly resolution, where each color represents a single reservoir within the network of 52 reservoirs. (Right Panel) Upper (red) and lower (orange) bound constraints for water year forecast at a weekly resolution.

Using EAGERS, we will run studies under various climate change scenarios in the Columbia River Basin and explore the effects of shifting energy demands, changing energy and water management infrastructure and raising the maximum instream flood control limits from Canada. We will then compare those scenarios to current and optimal management of the reservoir systems under current climate conditions. EAGERS outputs will also allow us to investigate the economic benefits and greenhouse gas emissions under these different scenarios, both within and beyond the Columbia River Basin boundaries. These results will give energy infrastructure managers a sense of the magnitude of changes they can expect in the future, as well as understand how shifting management of their energy sources and demands could impact the competing uses of water.

How Can Long-Term Water Storage Management Mitigate Problems in an Era of Resource Deficits?

Mengqi Zhao and Jan Boll

MANAGED AQUIFER RECHARGE (MAR) IS AN APPROACH TO STORING WATER THAT INCREASES WATER MANAGERS' FLEXIBILITY IN RESPONSE TO TEMPORAL VARIATIONS IN WATER SUPPLY AND DEMAND. WE DEVELOPED A SYSTEM DYNAMICS MODEL, VERIFIED IN THE YAKIMA RIVER BASIN, THAT ALLOWS USERS TO EXPLORE RECHARGE MANAGEMENT STRATEGIES AND EVALUATE HOW IRRIGATION RELIABILITY AND OTHER FACTORS OF INTEREST CHANGE IN RESPONSE.

Droughts in semi-arid regions of the United States are particularly impactful for communities and sectors that are already making efficient use of resources. Water use conditions in the Basin range from places where rivers, lakes and reservoirs are sufficient to provide water, to others where aquifers are the most stable water resource across seasons. While droughts may impact these places with different intensities, the risk of long-term water scarcity is greater when aquifers provide water today at the expense of tomorrow's supply. As the region faces population increases and increasing competition for water resources due to intensified connections between the food, energy, and water (FEW) sectors, the risk may increase further.

We have been asking questions about how to recharge aquifer systems to optimally achieve both short-term usage and long-term water supply sustainability. Managed aquifer recharge (Figure 1) is an innovative method we will evaluate that stores water during the snowmelt season into the aquifer, allowing users to pump it for irrigation during periods of water scarcity. To answer these questions, we first need to understand the interactions and feedbacks within the interconnected FEW system, to foresee the long-term consequences of current decisions. Then we can ask specific questions, such as 'Will implementing managed aquifer recharge improve the irrigation water reliability without affecting hydropower flow or environmental flow usage?' or 'How effective is managed aquifer recharge for maintaining sustainable water supply during future droughts?'



Figure 1. Managed Aquifer Recharge for Merti aquifer shared between Kenya and Somalia. The photo is from the Intergovernmental Authority on Development (IGAD).

Our team developed a system dynamics model that aims to capture historical behaviors of where and how much water is being allocated (based on historical data), and then to help answer 'what if' questions such as 'What extra amount of irrigation water would have been delivered if we implemented managed aquifer recharge five year ago?' The model quantifies physical processes, including how water moves throughout the water cycle (on the surface, in the soil and the aquifer). It also represents key socio-economic factors from markets, social norms, and policies (supply and demand, innovation adoption and water rights). We applied the model to the Yakima River Basin and compared calculated and observed streamflow data at the Parker gage station (below the City of Yakima) to verify whether or not it can capture down stream flow behaviors after reservoir operations seen in that Basin. With our

verified model, the user-friendly interface of the system dynamics model enables managers to evaluate, for instance, how much water is needed and how much water is available for irrigation in August, if they decide to withdraw 200,000 acre-feet of water from the river to recharge the aquifer in February.

The model allows users to explore dynamic storages, flows and feedbacks on the fly by dragging sliders of different variables (Figure 2). For example, the drought in 2015 caused severe impacts to the agricultural sector, where the water diverted to irrigation was only 47% of normal without transfers in the Yakima River Basin. Our model gives the user the ability to manage how much and when to recharge the aquifer and visualize how irrigation water reliability (irrigation supply to demand ratio) generally would improve in years like 2015, if those levels of recharge were implemented.

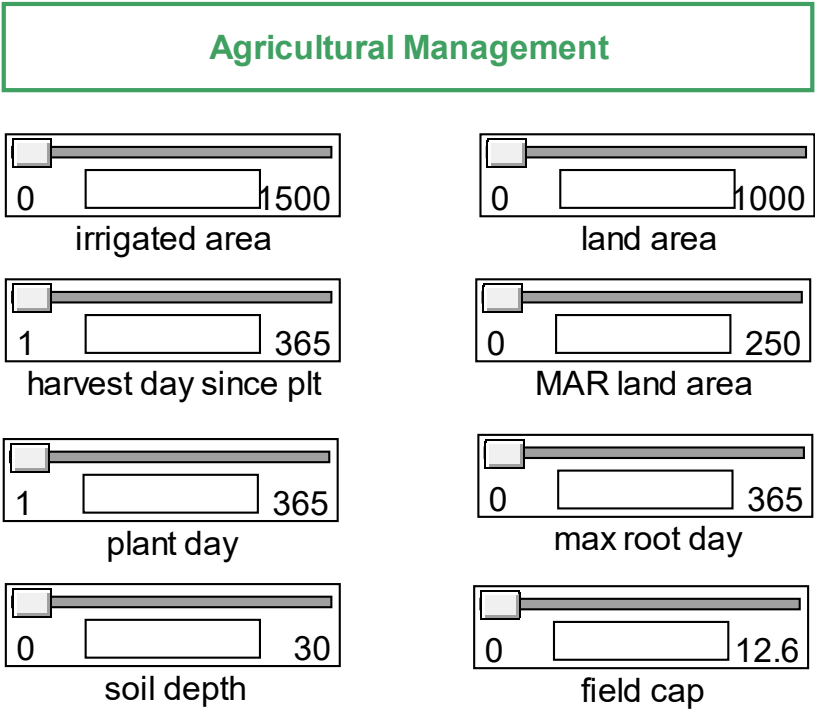


Figure 2. An example of management control panel for agricultural elements. Each slider controls a corresponding variable. By dragging the sliders, the results will be updated simultaneously in the output graphs, such as irrigation reliability.

How would different recharge decisions affect trade-offs within FEW sectors and between multiple years? We looked at one example, modeling multi-year MAR operations during successive drought events, and exploring the conflicts and trade-offs between pumping water for current use and saving water for future extreme droughts (Figure 3). The impact of consecutive two-year MAR application (operation 2) lasted longer than a one-year application (operation 1) or two separate one-year applications (operation 3). Multiple, consecutive-year applications of MAR (operation 4) increased the irrigation reliability in most years, and made up most of the water deficit in irrigation water supply.

As we gain greater understanding of the real-world particulars of MAR applications in basins like the Yakima River Basin, we aim to improve the confidence in the model's ability to represent aggregated, large-scale patterns that influence how water is managed across the Columbia River Basin. We welcome insights into the main features that characterize different regions across the Basin that may influence the effectiveness of MAR for reducing friction points between water uses in the FEW system as the climate changes.

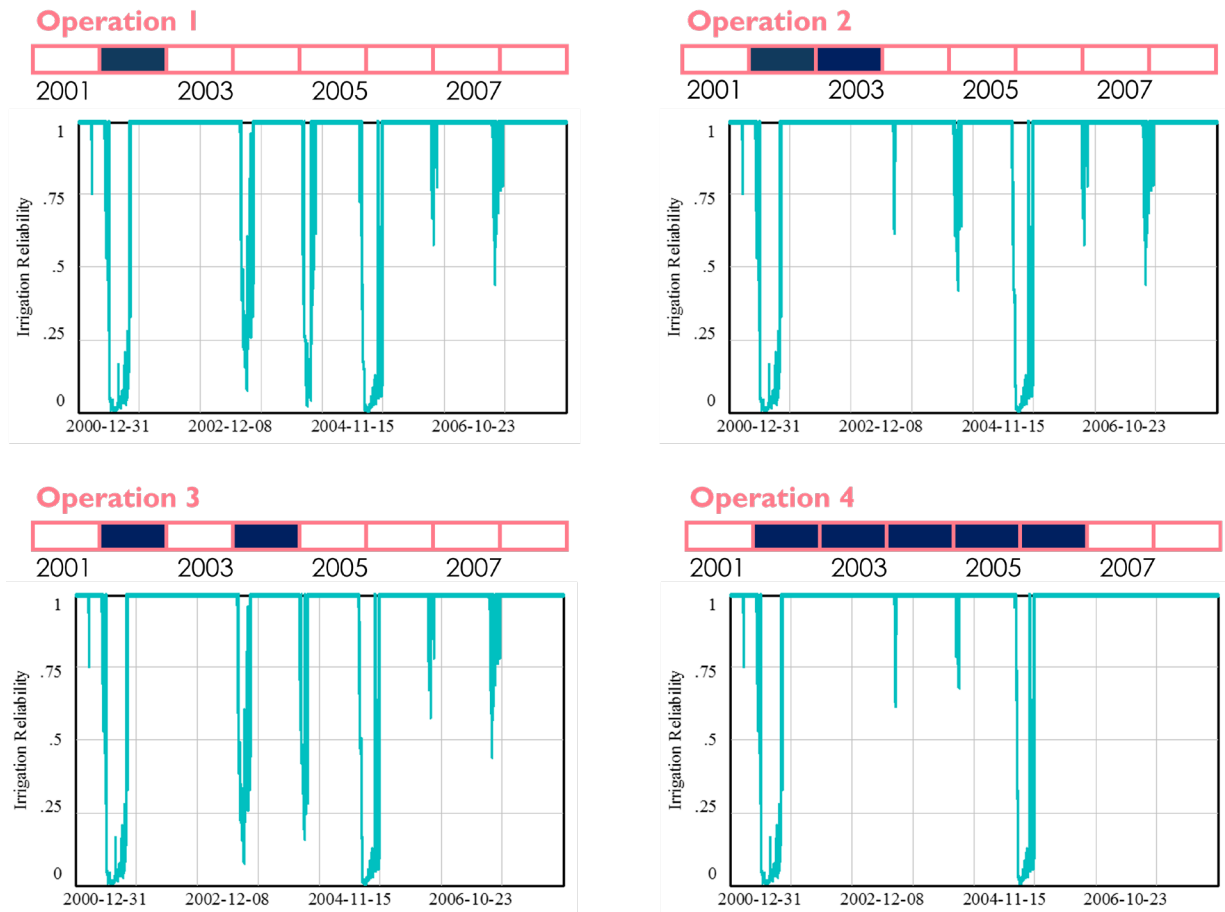


Figure 3. Four MAR operations and the corresponding changes for the irrigation reliability. The bar at the top of each graph shows the recharge operation that was modeled, with the black cells showing the timing of recharge. The graph shows the model output under that particular operation, for the period, from December 2000 through October 2008.

Technology for Trade: A Related Project on Food and Water Innovations in the Columbia River Basin

Georgine G. Yorgey, Jonathan Yoder, Kirti Rajagopalan, Sonia A. Hall, Jennifer C. Adam and Richael Young

IMPROVED INFORMATION TECHNOLOGIES, SUCH AS SEASONAL FORECASTING, CONSUMPTIVE USE MONITORING, AND COMPUTER-AIDED “SMART” WATER MARKETS, HAVE THE POTENTIAL TO INCREASE THE FLEXIBILITY OF WATER ALLOCATION IN THE COLUMBIA RIVER BASIN. THE TECHNOLOGY FOR TRADE TEAM IS WORKING TO DEVELOP THESE TECHNOLOGIES AND EXPLORE HOW THEY INTERACT WITH WATER MANAGEMENT LAWS, RULES, ADMINISTRATIVE PROCESSES, CONTRACTS AND OTHER INSTITUTIONAL FEATURES. TECHNOLOGY FOR TRADE IS NOT PART OF THE COLUMBIA FEW PROJECT, YET IS INCLUDED IN THIS REPORT GIVEN THE RELEVANCE OF THIS WORK TO OUR UNDERSTANDING OF THE INTERCONNECTED FOOD-ENERGY-WATER SYSTEM IN THE COLUMBIA RIVER BASIN.

In the Columbia River Basin, as in other basins across the western United States, water allocation decisions and processes are important for making the most of naturally variable water resources for diverse instream and out-of-stream purposes. Trade-offs inherently exist with so many competing uses for water, especially during drought years when available water is limited. Maximizing opportunities for water to be tasked to its highest valued potential use, both within agricultural systems and across its many competing uses, is important for making the most out of scarce water resources. New management approaches would be more effective with improved information, and emerging information technologies provide opportunities for enhancing the region’s resilience to drought by making water use more flexible. Such information-related innovations are already changing the legal and management landscape of water resources in the western U.S.

The Technology for Trade project, which will run from 2018 to 2023, is contributing to enhanced efficiency of water use by furthering the development of information technologies and complementary innovations in the rules that govern water use. In particular, the Technology for Trade team aims to further the development and application of three promising and complementary emerging technologies: improved seasonal forecasting, remote measurement of crop water consumption, and computer-aided ‘smart’ water markets (Figure 1). In addition, legal, regulatory and contractual innovations can be important to allow water users to use these technologies as effectively as possible while protecting the water rights of others.

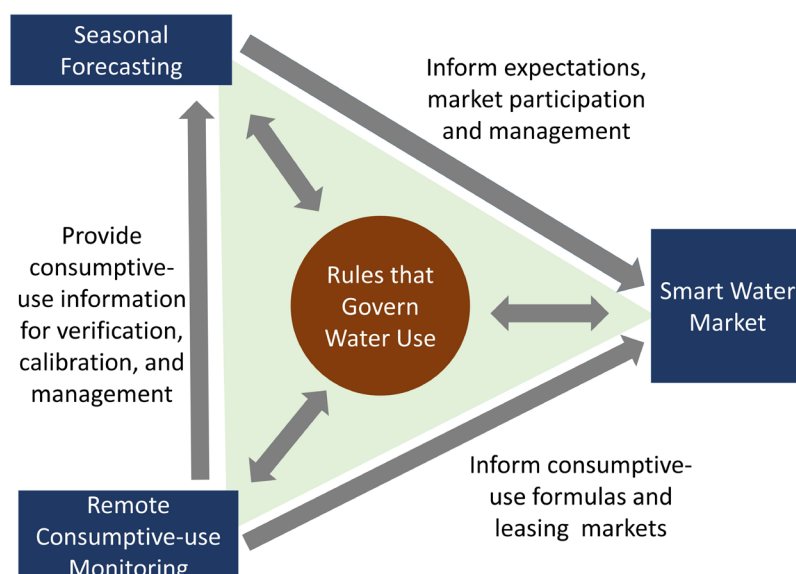


Figure 1. The three focal technologies of the Technology for Trade project complement each other, and provide information that, in combination with the rules that govern water use, creates new opportunities for water use.

Improved Seasonal Forecasting

The forecasting effort will utilize seasonal climate forecasts that are currently available with lead times of about eight months (i.e. the North American Multi-Model Ensemble), and will explore regional translation to forecasts of water availability and related metrics. The seasonal forecasting effort will identify when, where and what metrics can be

forecast with enough lead time, accuracy, and precision to be useful in decision-making. For example, improved seasonal water forecasting could help farmers plan their planting and water use activities earlier and with less uncertainty. Timely and informed decisions could then facilitate water transfers during times of shortage, including dry-year contracts (also called options contracts) or public reverse auctions to augment instream flows.

Remote Consumptive Use Measurement

The Technology for Trade team will develop and field-test a method to estimate plant evapotranspiration via METRIC—a method that calculates evapotranspiration from Landsat images of the surface using an energy balance approach. The method in development will use a combination of existing satellite data along with data collected by drones. Evapotranspiration is closely related to crop consumptive water use. The focus of this technology is thus irrigated agriculture, which is an important economic engine and accounts for the majority of regional out-of-stream consumptive water use. This technology can provide a spatially explicit (e.g. 30 m x 30 m), estimate of water stress or crop water use, which might be used to better guide variable rate irrigation systems and improve yields. During dry years, consumptive use measurements could support improved deficit irrigation strategies, and perhaps partial leasing of water rights. At a basin scale, satellite-based imagery could help protect water rights against increases in consumptive use elsewhere in a watershed, and complement existing water metering efforts.

Computer-Aided ‘Smart’ Water Markets

The ‘smart’ water markets effort will tailor existing water trading software technology (from Mammoth Trading) to three watersheds within the Columbia River Basin (Figure 2), to reflect their unique legal and hydrological conditions, as well as specific trading goals identified within the watersheds. Smart markets ease the process of matching multiple sellers and buyers of water and help navigate the highly complex regulatory constraints for a successful trade. This could facilitate temporary transfers during times of shortage to the most valuable uses, both instream and out-of-stream, in ways that do not impair other water users.

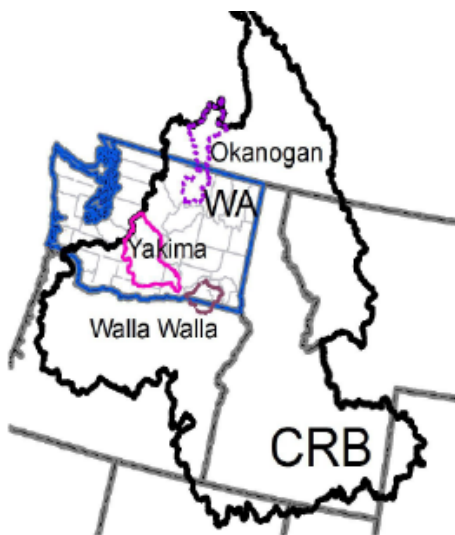


Figure 2. While these technologies and institutional innovations have the potential to be relevant across the Western U.S. and beyond, our focus in the Technology for Trade project is on three diverse watersheds in the Columbia River Basin (CRB) where water is in economic demand, and water security is of concern: the Yakima, the Walla Walla, and the Okanogan watersheds.

The usefulness of these technological innovations will be affected by the flexibility of water use law, regulation and other factors that frame water allocation decisions. The Technology for Trade project will therefore explore how changes in legislative and administrative rules, contracts and norms could change the context and incentives surrounding water use and allocation. The goal is to identify and explore how complementary changes in these factors could enhance the effectiveness of the technologies for helping water managers meet multiple, diverse demands for water.

This 5-year research and extension project (2018-2023) is led by Washington State University's State of Washington Water Research Center (WRC) and is supported by USDA National Institute of Food and Agriculture, project #1016467. The full Technology for Trade project team, and more information about the project, is available at <https://wrc.wsu.edu/project/technology-for-trade/>.

The Columbia River Treaty between the United States and Canada

Barbara Cosens

ONGOING DISCUSSIONS AROUND RENEGOTIATING THE COLUMBIA RIVER TREATY COULD BE AN IMPORTANT DRIVER OF CHANGE IN CERTAIN ASPECTS OF THE COLUMBIA RIVER BASIN'S FOOD-ENERGY-WATER SYSTEM. THIS ARTICLE, ADAPTED FROM AN ARTICLE PUBLISHED IN THE ADVOCATE (2017), PROVIDES AN OVERVIEW OF THOSE DISCUSSIONS, AS CONTEXT FOR OTHER ARTICLES IN THIS PROGRESS REPORT.

Some Background on the Columbia River Treaty

The United States and Canada have operated the mainstem of the Columbia River jointly since the Columbia River Treaty entered into force in 1964. Under the Treaty, Canada agreed to build three new dams to provide 15.5 million acre feet (MAF) of storage. The United States agreed to pay Canada \$64.4 million for dedication of 8.45 MAF of that storage to assure flood control for sixty years and to share the added benefits from hydropower generation in the United States, resulting from the release of water from three reservoirs (referred to as the "Canadian Entitlement"). The U.S. Congress authorized construction of the Pacific Northwest-Pacific Southwest Intertie, which led to an interconnected North American electric grid. The provincial utility, BC Hydro, entered into thirty-year contracts for sale of the Canadian Entitlement to utilities in the U.S. Southwest. BC Hydro continues to sell that power on the U.S. market following expiration of the contracts. The Treaty also allowed, but did not require, the United States to build a dam on the Kootenai River (spelled Kootenay in Canada) that would back water up into Canada. The United States exercised this option when it built Libby Dam.

The U.S. and Canada could, at any time since the Treaty entered into force, mutually agree to modify or terminate the Treaty. It is the expiration of the sixty-year period of assured flood control on September 16, 2024, combined with a Treaty provision allowing either country to unilaterally walk away from the Treaty beginning on that same date, given 10 years notice, that has triggered a broad review of the Treaty.

The U.S. Army Corps of Engineers and the Bonneville Power Administration led the regional review in the United States, and British Columbia led the review in Canada. The U.S. Regional Review included the establishment of a sovereign review team, composed of one representative from each of the four main states in the Basin, five representatives of the 15 Native American tribes, and representatives of the 11 federal agencies with interest in the Basin. The sovereign review team also had comparable representation on a technical advisory body. Listening sessions were held throughout the Basin to obtain input from other interest groups and the general public. In a remarkable act of intertribal diplomacy, the 15 Native American tribes in the Basin came together to develop a set of "Common Views" on the future of the Columbia River and continued to work in concert throughout the process. This sophisticated act of diplomacy influenced the outcome of the review process and was not matched by the states. The British Columbia review process included extensive public engagement and consultation with the First Nations claiming resources in the Basin. On December 13, 2013, the U.S. Entity transmitted the Regional Recommendation to the U.S. Department of State, and on March 13, 2014, British Columbia announced its position on the future of the Treaty.

The United States Entity Regional Recommendation outlined three primary goals for modernization of the Treaty:

- 1) To elevate ecosystem function to a third primary purpose of international cooperation, along with hydropower and flood control;
- 2) To amend the formula for sharing of power benefits to more closely reflect actual operations; and
- 3) To continue to cooperate on the development of a flood risk management plan that reflects, among other things, the implications of climate change.

Although the Treaty currently does not address apportionment of water supply or navigation, the Recommendation calls for acknowledgement of the importance of each. It also calls for the flexibility to seek mutual benefits in use and development of storage for out-of-stream use. The Recommendation responds to the call for greater public and sovereign participation by recommending the formation of an advisory body for negotiations and reconsideration of the composition of the U.S. Entity for implementation of the modernized Treaty.

The provincial government of British Columbia seeks to “[c]ontinue the Columbia River Treaty and seek improvements within the existing Treaty framework,” and sets forth 14 principles including:

- 1) Recognition that shared benefits go beyond hydropower production and that British Columbia should be compensated accordingly;
- 2) Recognition that the impacts of the Treaty dams on Canada are ongoing and should be compensated; and
- 3) A greater use of U.S. storage for flood control and thus a reduced reliance on Canada.

While the Province supports continued efforts to cooperate on ecosystem function, it does not view this as a component that requires change to the Treaty. Canada has yet to appoint a lead for the Treaty negotiations.

Negotiations between the United States and Canada began in May 2018. Public meetings are being held periodically throughout the Basin. The negotiating team for the United States is composed as follows:

The U.S. negotiating team will be led by the U.S. Department of State and will include the Bonneville Power Administration and the U.S. Army Corps of Engineers Northwestern Division (which together comprise the “U.S. Entity” that implements the Treaty in the United States); the Department of the Interior; and the National Oceanic and Atmospheric Administration (US Dept. of State, 2018).

Canada is represented by the Foreign Ministry and the Province of British Columbia, due to the special role in Treaty implementation as a result of a 1964 agreement between the federal government and the province.

The Relation Between the Columbia River Treaty and the Columbia FEW

Modeling was used during the Treaty review process to explore possible outcomes with and without negotiation of a modernized Treaty. This modeling was driven, appropriately, by the questions arising from the main purposes of the Treaty. These purposes do not include out-of-stream water uses such as irrigation for food production, and impacts on agriculture were therefore not the focus of the agencies’ modeling. Our Columbia FEW team’s interest in the interconnected nature of food and water in the Columbia River Basin led us to assess the impacts of possible Treaty changes (in the context of climate change) on agriculture (see Rushi et al.’s article).

Additional Resources

Please see the following resources for additional and updated information on the renegotiation of the Columbia River Treaty:

United States: Information and a means to make inquiries can be found at <https://www.state.gov/p/wha/ci/ca/topics/c78892.htm>. Information on the modeling that informed the Treaty review process can be found at the Technical Studies section of the US review, <https://www.crt2014-2024review.gov/TechStudies.aspx>.

Canada: Information can be found at <https://engage.gov.bc.ca/columbiarivertreaty/>. Comments can be made through a link on this website and interested persons may sign up for updates.

References

US Department of State, Office of Spokesperson (May 22, 2018). Launching Negotiations to Modernize the Columbia River Treaty Regime. Available at: <https://www.state.gov/r/pa/prs/ps/2018/05/282388.htm>

The majority of this article is modified and updated with permission from: Cosens, B. August 2017. Modernization of the Columbia River Treaty: an Opportunity for Idaho. The Advocate (a publication of the Idaho State Bar). Please refer to the original article, available online at <https://isb.idaho.gov/wp-content/uploads/August-2017-Book.pdf#page=34>, for a full list of references, which were not included here for simplicity.

Potential Impacts of Climate Change and the Columbia River Treaty Renegotiation on the Food-Energy-Water System

Begum Rabeya Rushi, Jennifer C. Adam, Muhammad Barik, Se-Yeun Lee, Kirti Rajagopalan, Michael Barber, Michael P. Brady, Jan Boll and Barbara Cosens

EXTERNAL FACTORS, LIKE CLIMATE CHANGE, AND INTERNAL ONES, LIKE THE RENEGOTIATION OF THE COLUMBIA RIVER TREATY, CAN IMPACT AGRICULTURAL PRODUCTION IN THE COLUMBIA RIVER BASIN. WE ASSESSED THESE POTENTIAL IMPACTS AND FOUND THAT, ALTHOUGH CLIMATE CHANGE IS PROJECTED TO CHANGE THE AMOUNT AND TIMING OF UNMET IRRIGATION DEMAND DURING DROUGHT YEARS, THE IMPACTS CAN BE EITHER EXACERBATED OR ALLEVIATED BY TREATY MODIFICATIONS.

How will external factors, like climate change, and internal ones, like the renegotiation of the Columbia River Treaty, interact across the Columbia River Basin? Answering this question can help natural and agricultural resource managers enhance the system's ability to adapt to these changes. While the original Treaty was focused on hydropower and flood control, regional stakeholders are recommending that modernization of the Treaty elevate ecosystem function to a third primary purpose (see Cosens' Treaty article). Out-of-stream water uses, such as irrigation, are not being recommended as a primary purpose for the Treaty, so the agencies involved have not evaluated impacts of renegotiation to food production. Our objective was therefore to assess the impacts of possible Treaty changes on agriculture, in the context of climate change.

We used an integrated model (Figure 1) to quantify water supply, water demand, and water availability for agriculture along the Columbia River mainstem, under two alternative Treaty scenarios that differed in the amount of storage available and ten climate change scenarios. While the integrated model's main components—VIC (Liang et al. 1996), CropSyst (Stockle et al. 2014), and ColSim (Hamlet and Lettenmaier 1999)—have been used for numerous applications, this work included a new module to simulate water rights curtailment, which occurs when there is not enough water in the stream to support all water rights and so the most junior of the rights is interrupted ("curtailed"). By considering out-of-stream (irrigation plus municipal) and state-adopted instream flow rules, we estimated the frequency and magnitude of curtailed irrigation water rights at various locations along the Columbia River mainstem. We also quantified unmet irrigation demand, which is defined as the volume of water not provided for irrigation due to curtailment.

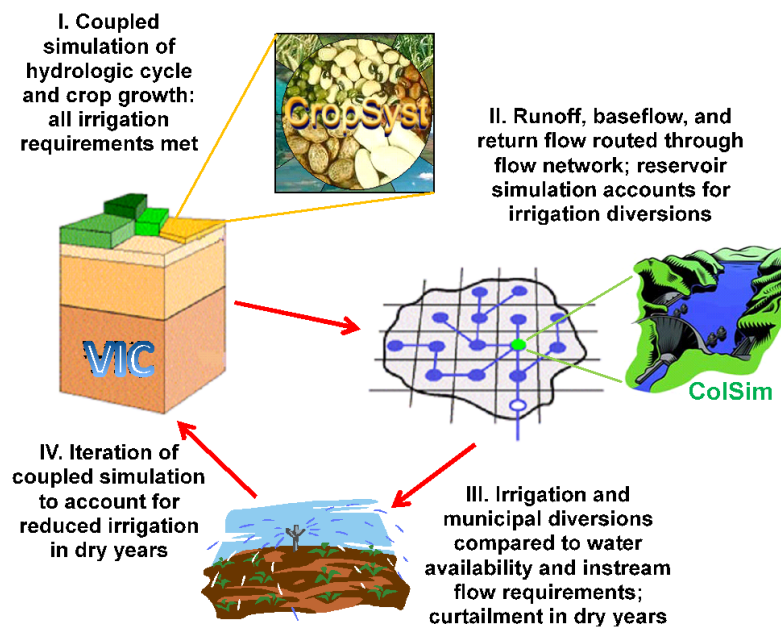


Figure 1. Diagram of the biophysical modeling framework (Stöckle et al. 2014) used for this study, involving VIC-CropSyst (Malek et al. 2017), a reservoir operation modeling tool, ColSim (Hamlet and Lettenmaier 1999), and a water rights curtailment model (Rajagopalan et al., in prep.).

The two alternative Treaty scenarios we considered, obtained from Bonneville Power Administration documentation (BPA, personal communication), focus on planned storage for flood risk and flow augmentation for water supply and ecological purposes:

Scenario I: Provides extra planned storage in Arrow Lakes (Keenleyside Dam) to keep the flood risk level the same as current conditions.

Scenario II: Along with Arrow storage, additional storage is proposed for Mica.

Both scenarios were simulated to store more water during the winter for release in the spring and summer for ecosystem uses and irrigation water supply at The Dalles.

Five climate change scenarios for each of two emissions scenarios (moderate and high, as defined by the IPCC's Representative Concentration Pathway 4.5 [RCP4.5] and 8.5 [RCP8.5]) were considered, for 30-year periods centered on the 2030s and the 2060s. The scenarios that were selected were selected to span a range of high-to-low precipitation and temperature changes, and allow us to examine how river flow might respond to a range of potential climate futures.

Crop yields are impacted by climate change due to a combination of changes to seasonal water supply, irrigation water demand, and farmer behavior. In response to a reduction in the snowpack, we expect a shift in water supply towards earlier in the season, with higher flows occurring from January through April and comparatively lower flows during the summer months (Figure 2, top panel). Climate change causes irrigation demand to shift earlier in the season, as warming allows earlier planting of annual crops, which also complete their growth cycle more quickly (Figure 2, bottom panel). This reduces the length of the irrigation period and causes much of the irrigation to occur earlier in the season (Figure 2, bottom panel). In some cases, this shift in irrigation demand outpaces the shift in water supply, resulting in increased curtailment early in irrigation season. If irrigated crops are mainly annuals (which exhibit this behavior) rather than grasses and other perennials (which do not; Rajagopalan et al. 2018), these shifts could lead to reduced curtailment later in the irrigation season. Note, however, that some adaptive actions taken by farmers (e.g., double cropping and the planting of slower maturing crop varieties) would extend the irrigation demand later into the season (see Rajagopalan et al.'s adaptation article).

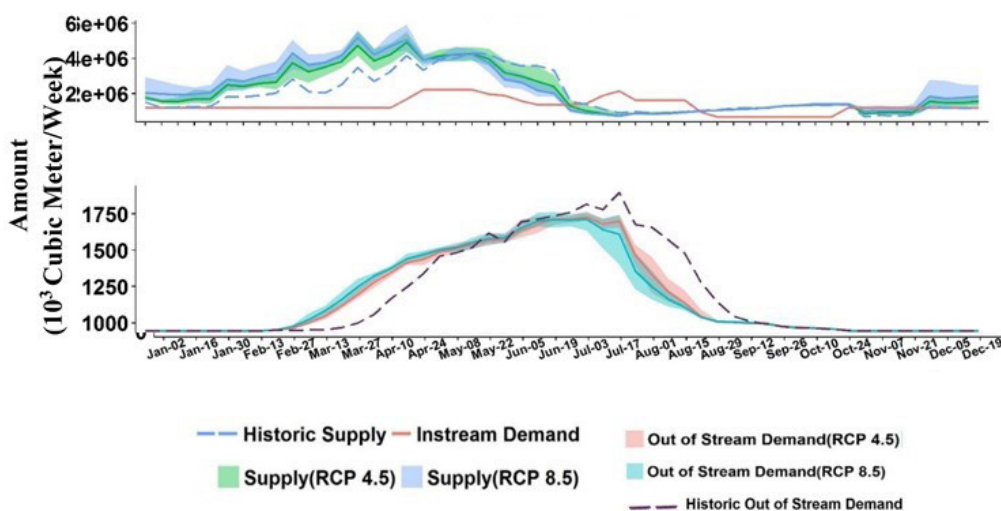


Figure 2. Impacts of climate change. Water supply and instream flow requirement (top), and out-of-stream water demand (bottom) at the Priest Rapids Dam for the historical and 2060s climates. Note that RCP 4.5 (8.5) represents the lower (higher) greenhouse gas emissions scenarios. These results are for no change in the Columbia River Treaty.

Simulations show that the Treaty has the potential to impact irrigated crop yields along the mainstem. Both Treaty scenarios reduce the magnitude of unmet demand in a historical climate (Table 1). However, they can either exacerbate or alleviate the impact of climate change on crop yields. Scenario II, which allows for the greatest increase of storage, is shown to be most beneficial for irrigation water supply, as additional storage can redistribute water from the winter season of surplus to the irrigation season of deficit. Scenario I, on the other hand, mostly leads to increased unmet irrigation demand under future climate scenarios (red values in Table 1). Therefore, irrigated crop yield should be considered along with flood risk, hydropower generation, and ecosystem function to provide a more comprehensive analysis of Treaty modifications on the food-energy-water system.

Table 1. Impacts of Treaty modifications in the context of climate change. Percent change in annual mean unmet irrigation demand at key dams along the Columbia mainstem in response to climate (using the median value among future climate scenarios) and Columbia River Treaty scenarios. The percent changes are calculated using historical climate and current Treaty operations as the baseline. Therefore, negative values mean that curtailment of interruptible irrigation water rights is reduced, while positive values mean that curtailment is increased in comparison to the baseline scenario.

Treaty Scenarios	Period	Emissions Scenario	Percent change given alternative Treaty scenarios (%)					
			McNary	Priest Rapids	Wanapum	Rock Island	Rocky Reach	Wells
Scenario I	1981-2010	Historical	-2.49	-1.84	-2.54	-2.53	-2.34	-2.21
	2030s	RCP 4.5	0.13	-0.58	0.26	0.26	0.39	0.39
		RCP 8.5	0.57	0.1	1.02	1.02	1.20	1.19
	2060s	RCP 4.5	0.01	-0.43	0.09	0.09	0.24	0.21
		RCP 8.5	0.42	0.003	0.37	0.37	0.47	0.39
Scenario II	1981-2010	Historical	-3.97	-0.42	-3.21	-3.21	-3.00	-2.95
	2030s	RCP 4.5	-1.31	-0.97	-1.14	-1.14	-1.27	-1.39
		RCP 8.5	-0.78	-0.23	-0.35	-0.35	-0.32	-0.37
	2060s	RCP 4.5	-1.66	-1.1	-1.61	-1.61	-1.59	-1.39
		RCP 8.5	-0.84	-0.89	-1.16	-1.16	-1.15	-1.17

References

- Liang, X., Wood, E.F. and Lettenmaier, D.P., 1996. Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification. *Global and Planetary Change*, 13(1), pp.195-206.
- Malek, K., C.O. Stöckle, R. Nelson, K.J. Chinnayakanahalli, Liu, M., Rajagopalan, K., Barik, M., and J. C. Adam, 2017. VIC-CropSyst: A regional-scale modeling platform to simulate the nexus of climate, hydrology, cropping systems, and human decisions, *Geoscientific Model Development*, doi: 10.5194/gmd-10-3059-2017.
- Rajagopalan, K.R., K. Chinnayakanahalli, C.O. Stockle, R. Nelson, A. Hamlet, M. Brady, M. Barber, C. Kruger, K. Malek, G. Yorgey, S. Dinesh, and J.C. Adam, 2018. Impacts of near-term regional climate change on agricultural production in the Columbia River basin. *Water Resources Research*: doi: 10.1002/2017WR020954.
- Stöckle, C.O., A.R. Kemanian, R.L. Nelson, J.C. Adam, R. Sommer, B. Carlson, 2014. CropSyst model evolution: From field to regional to global scales and from research to decision support systems, *Environmental Modeling and Software*, 62, 361-369.
- Vano, J. A., Kim, J. B., Rupp, D. E., and Mote, P. W., 2015. Selecting climate change scenarios using impact-relevant sensitivities. *Geophysical Research Letters*, (4213), 5516-5525.

5: Tying the Pieces Together

Conceptual Mapping: How We Visualize the Columbia River Basin, a Large-Scale, Complex, Food-Energy-Water System

Julie C. Padowski, Jan Boll and Sasha Richey

THE FOOD-ENERGY-WATER (FEW) SECTORS IN THE COLUMBIA RIVER BASIN FORM AN EXAMPLE OF A COMPLEX SYSTEM, WITH A MULTITUDE OF COMPONENTS AND CONNECTIONS THAT DYNAMICALLY INTERACT. THE COLUMBIA FEW TEAM IS WORKING TO UNDERSTAND HOW CHANGES FROM OUTSIDE AND WITHIN THE SYSTEM INFORM THE WAY WE MANAGE FOOD, ENERGY AND WATER RESOURCES AND HOW WE CAN CREATE WIN-WIN OUTCOMES FOR ALL WORKING AND LIVING IN THE BASIN. CONCEPTUAL MAPPING IS ONE WAY TO ORGANIZE THE COMPLEXITY OF A SYSTEM, ALLOWING USERS TO VISUALLY SEE THE ENTIRETY OF THE ASSOCIATED SYSTEM COMPONENTS AND INTERCONNECTIONS. THIS IS A USEFUL FIRST STEP FOR INFORMING MODELING EFFORTS, DATA COLLECTION, AND SCENARIO DEVELOPMENT IN THIS PROJECT.

The Columbia River Basin is a large watershed with dynamic, interacting food-energy-water (FEW) sectors interlinking agriculture, hydropower, ecosystems and its social fabric. Climate change and continued population growth are expected to create significant perturbations to this FEW system, which tax the existing components and connections within the system. The Columbia FEW project explores how potentially negative impacts of such perturbations can be anticipated, absorbed or reversed, either through technological or institutional innovations, and how these innovations can provide win-win-win outcomes across the FEW system. The project uses many different models to develop our collective understanding of the connections between the environmental and human components of the Columbia River Basin (see Adam et al.'s article). We also explore future scenarios (e.g., population growth and associated water and energy demands, changes in rainfall and temperature, changes in crop variety or agricultural area) and the impact of changes or innovations (e.g., strategic management of surface water and groundwater, integration of renewable sources into energy supply portfolios) on the complex array of individuals, communities and managers, as well as social and biophysical processes and constraints of the Columbia River Basin's complex FEW system.

As a first step to understand and describe this complex system, we dedicated substantial effort towards creating a conceptual map that represents it. This mapping exercise involved FEW team members with academic expertise in food, water, energy and social systems, and integrated knowledge from across these and other disciplines (Figure 1). The goal was to identify:

- 1) Storage components and connections in each FEW sector,
- 2) How each FEW sectors interact with each other and are impacted by external forces such as climate change,
- 3) Potential friction points, or challenges in the system, and
- 4) Portions of the system that were well represented by measurements, data, or models, and which portions needed model improvements.

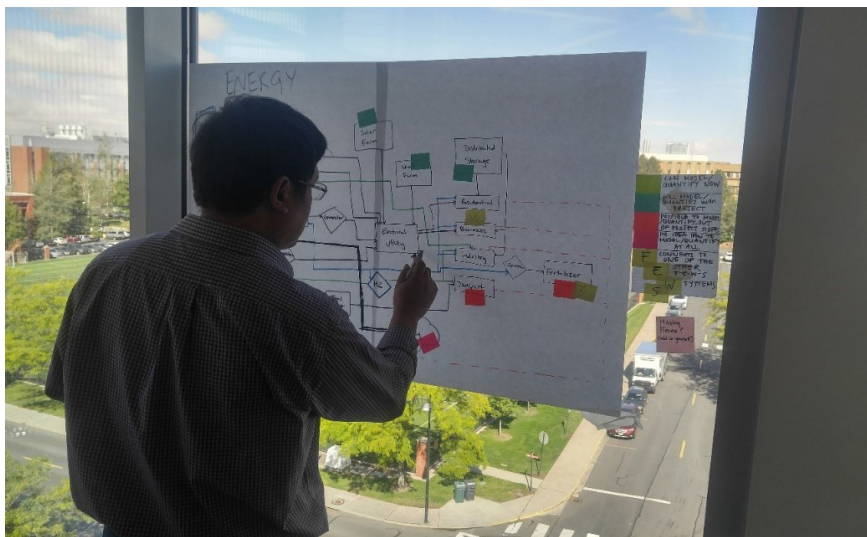


Figure 1. Team members add their knowledge about food, energy and water sectors to draft conceptual maps of the Columbia River Basin's food-energy-water (FEW) system.

Each FEW sector and the social system were first mapped individually (see the water sector in Figure 2), and then these maps were merged to create a comprehensive conceptual map of the FEW system (Figures 3 and 4).

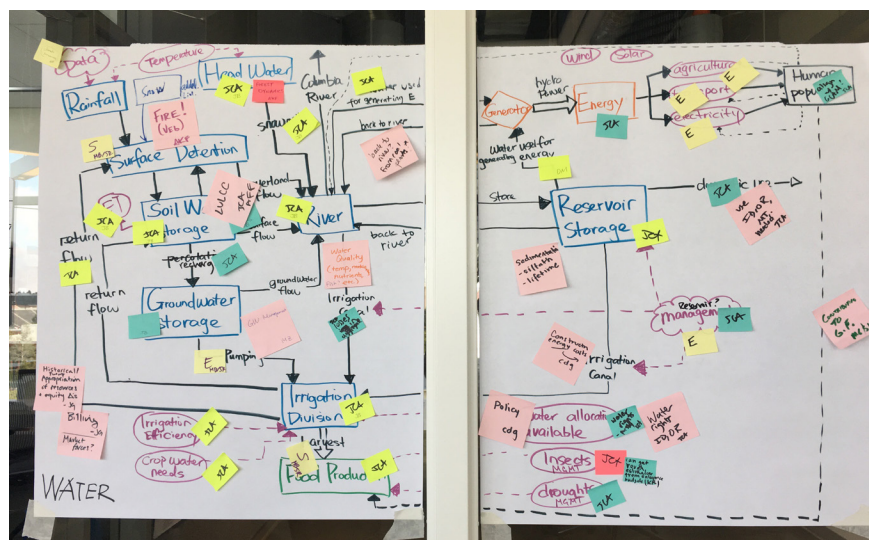


Figure 2. A detailed map of the Columbia River Basin's water sector, including major components, how they interact, and where representative data for modeling pieces of this system exist.

Various teams within this FEW project have been using parts of the conceptual map in different ways. For example, the core modeling group is using the map to identify places in existing models where new linkages need to be added, or where data gaps need to be filled. The group focused on innovations is using the conceptual map to evaluate broader patterns of change in the FEW system, identifying where critical friction points or challenges could benefit from new innovations or solutions, and where adjustments to one sector may create unintended consequences for other sectors, communities, or environmental systems within the larger FEW system (see Zhao and Boll's article on water storage management, and Maureira et al.'s article on greenhouses). A clearer understanding of the dynamics and connectivity of the FEW system is providing researchers with better insights into what aspects of a FEW system are important across many spatial or temporal scales, and which aspects are unique at only one scale. This in turn is helping the team create performance indicators and meaningful resilience metrics to develop a STAR Calculator (see Richey et al.'s article). The Calculator will be used to measure how well the FEW system is currently performing and to evaluate the impact of different innovations in enhancing the sustainability and resilience of the Columbia River Basin.

The conceptual map so far has played a key role in multiple aspects of the Columbia FEW project. Upcoming uses for the conceptual map in 2019 will revolve around building flexible system dynamics models. System dynamics models are being developed to explore the biophysical and economic impact of new innovations, and build on the representation of system complexity developed during the team's mapping efforts. Other projects will use the relationships captured by the conceptual map to lay a foundation for understanding what drives innovation uptake in different communities and sectors. Further development and refinement of individual sectors' and the comprehensive FEW system map will continue as new data and insights from different team endeavors emerge, and we will continue to use this map to identify effective target solutions that enhance the resilience of the FEW system in the Columbia River Basin.

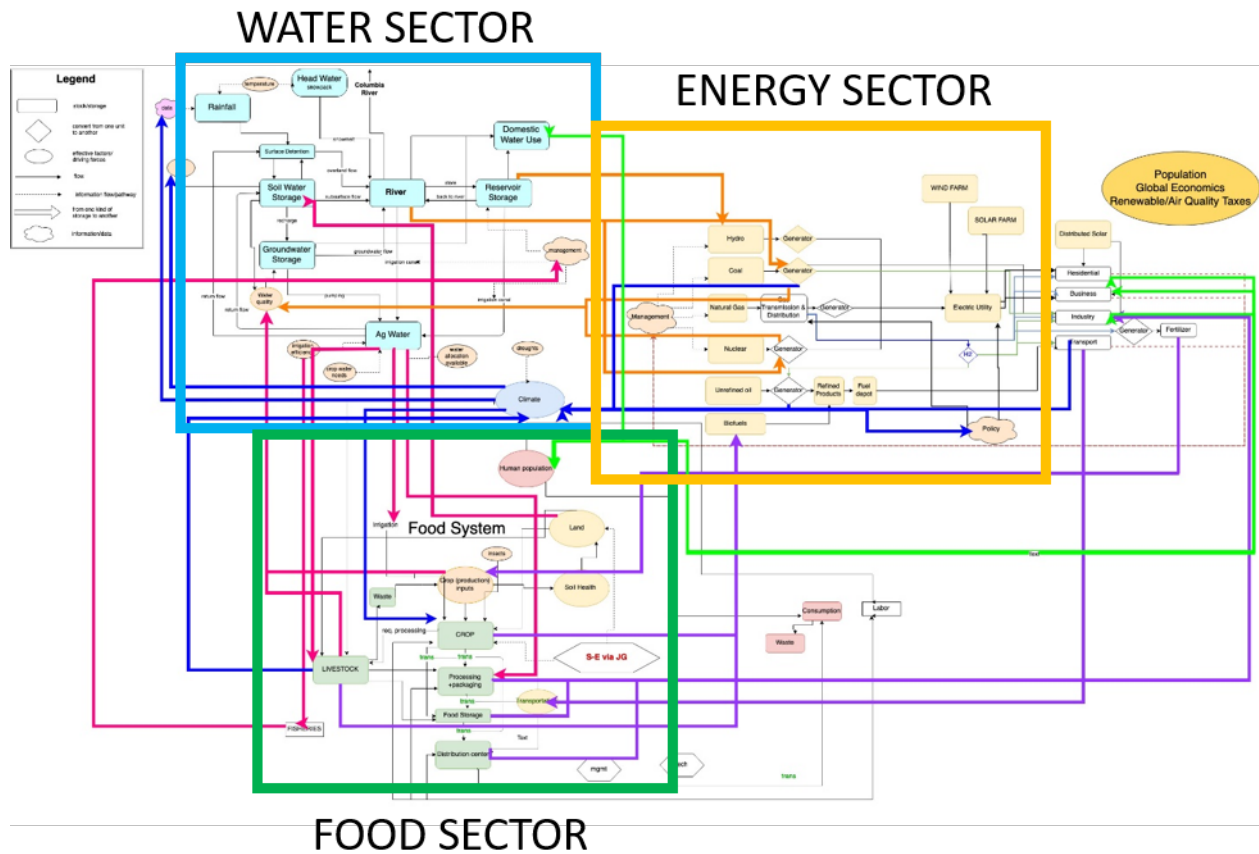


Figure 3. Draft conceptual map of the Columbia River Basin food-energy-water (FEW) system, showing the complexity of components and interconnections. Key elements are clearer in Figure 4, showing (A) the water sector, (B) the food sector and (C) the energy sector.

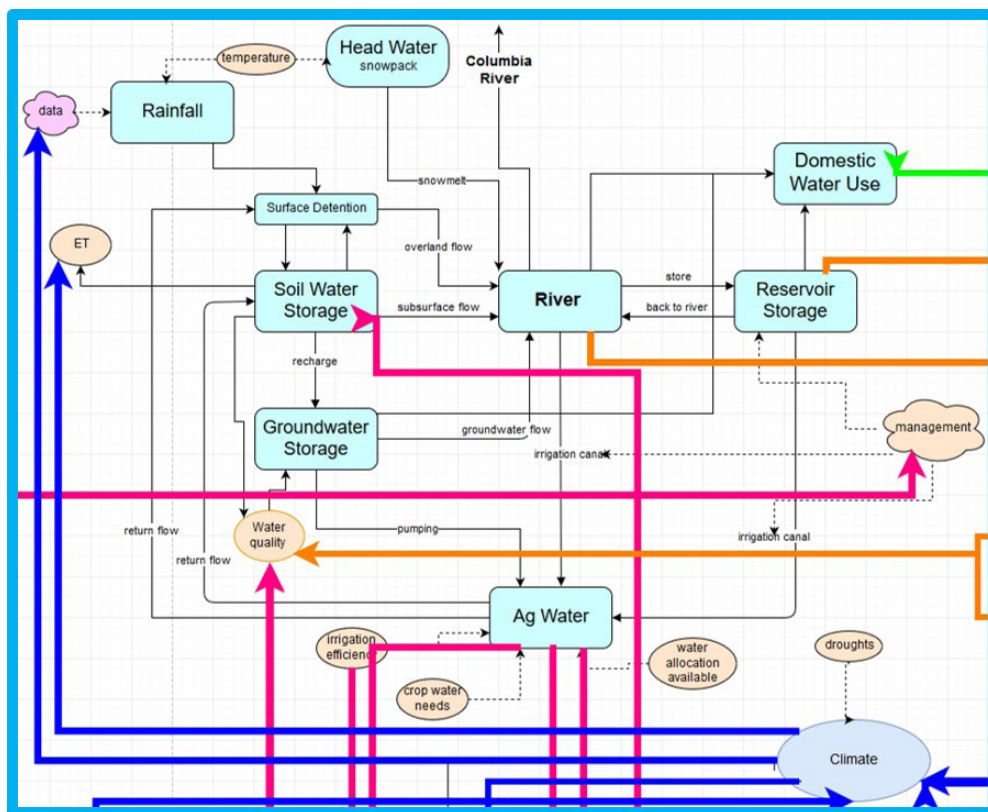


Figure 4A. The water subsystem, including natural hydrology and managed water infrastructure.

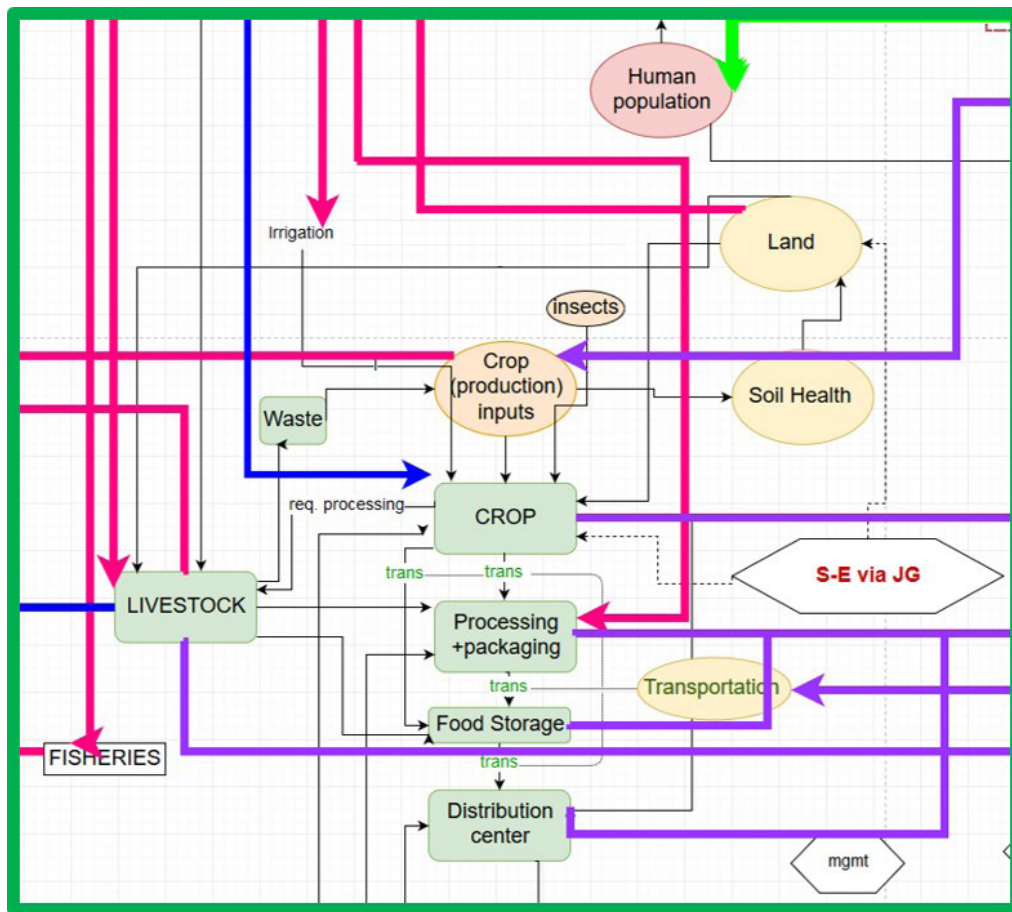


Figure 4B. The food subsystem, including crop production, processing and distribution activities.

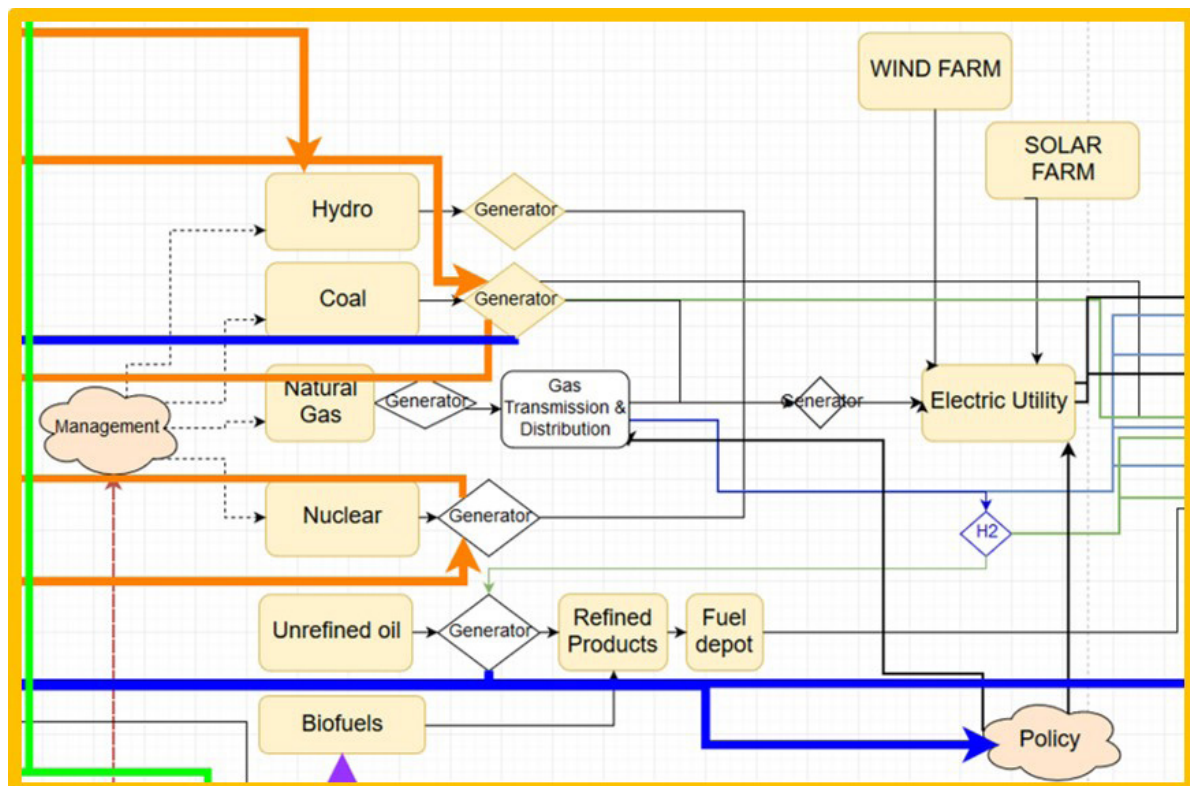


Figure 4C. The energy subsystem including, energy sources and human energy production and distribution infrastructure.

Understanding How to Assess Resilience in Human-Natural Systems

Julie C. Padowski and Stephanie Hampton

ACHIEVING RESILIENCE IN PRACTICE REQUIRES A COMMON GOAL AND UNDERSTANDING BY MANAGERS, SCIENTISTS AND COMMUNITY MEMBERS ABOUT HOW THEIR SYSTEM CHANGES OVER TIME, WHAT CAUSES THESE CHANGES, AND WHERE AND HOW NEW INNOVATIONS OR PRACTICES CAN BE IMPLEMENTED TO ALTER THE TRAJECTORY OF THE SYSTEM FOR A BETTER FUTURE. WE WORKED WITH A RESILIENCE EXPERT TO UNDERSTAND HOW TO MEASURE RESILIENCE IN THE FOOD-ENERGY-WATER SYSTEM OF THE COLUMBIA RIVER BASIN.

Resilience is a system property that describes the tendency of a system to maintain structure and function following perturbation, and is an important attribute for assessing and dealing with an uncertain or changing future. So how do we build a resilient food-energy-water (FEW) system? In March 2018, we invited Paul Ryan, Director of the Australian Resilience Centre (<https://www.ausresilience.com.au>), to discuss how to assess complex human-natural systems and build knowledge and capacity to achieve a desired long-term vision for a resilient food-energy-water system. Ryan's approach stresses the importance of integrating local knowledge and values with quantitative data to identify the underlying problems that make a system susceptible to shocks and to develop strategies for addressing these hurdles.



Figure 1. Framing resilience in the Columbia River Basin. Team members collectively identified FEW system aspirations and hurdles to create a conceptual model of what a resilient Columbia Basin FEW may look like.

Over the course of two days, Ryan worked with us to show how he structures and runs resilience assessments, using the intersection of issues and synergies between the food, energy, and water sectors in the Columbia River Basin as a working example (Figure 1). These assessments consisted of three key stages:

- 1) **Defining goals and information.** Ryan uses various strategies to develop consensus around desired end points in diverse groups and complex systems. A clear purpose and scope identified early on, and adequate information about the system to be managed, are key for engaging and retaining the right set of stakeholder partners and initiating actionable change (Figure 2).

- 2) **Characterizing the system.** This step identifies not only the surficial problems that stakeholders are hoping to address, but also creates understanding of the underlying patterns, system structure, and larger paradigms that shape the potential future pathways for system change (Figure 3). For instance, a drought is a system shock that can have a negative impact on agricultural production, reducing expected yields and lowering profits. This shock is an easily identifiable challenge, but understanding what causes droughts (changes to climatic patterns), why droughts are so impactful (our agricultural system operates with an expectation of ample water each year), and how we can reframe how we manage for droughts (how could we alter our agricultural system to suffer less in a drought-filled future) are all key for improving agricultural resilience (Figure 3).
- 3) **Identifying key processes, stakeholders, and friction points within the system.** Ryan presented system dynamics as a framework to help stakeholders identify areas where innovation is needed to overcome challenges. We drafted the Columbia River Basin FEW system and what “optimal” resilience in the Basin may look like, and explored the impact of different “futures” on system-wide resilience goals.

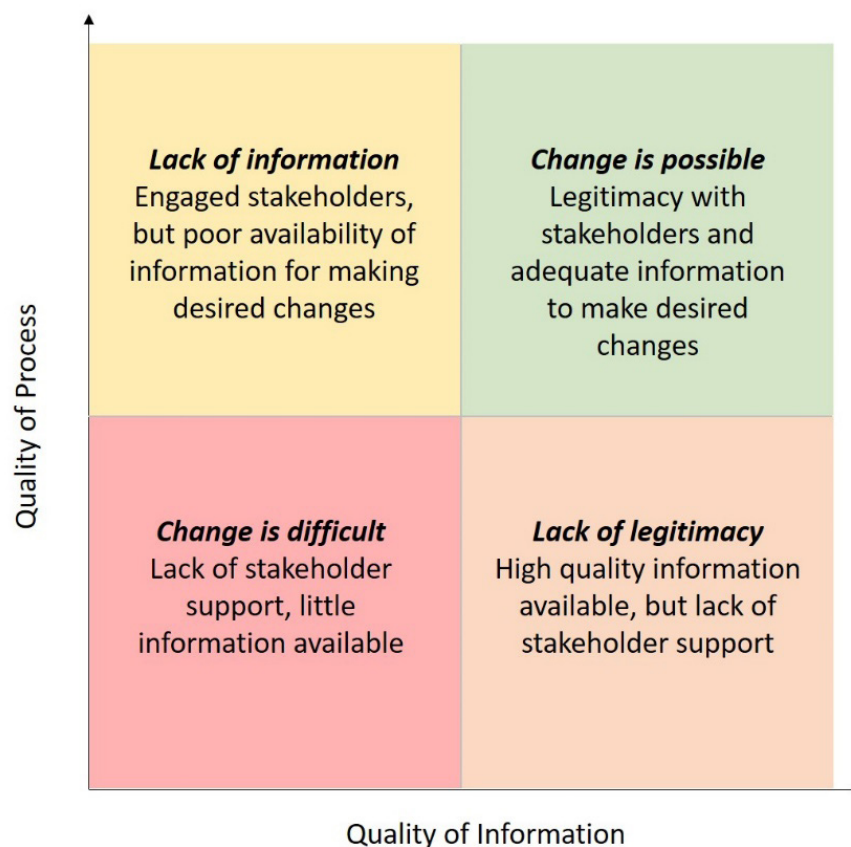


Figure 2. Successful resilience assessments require both good information and engaged stakeholders. Deficiencies in one or the other can limit the effectiveness of assessment outcomes, or lead to decisions or actions that are misguided or inappropriate for the desired end-goal (adapted from Enfors-Kautsky, E., Järnberg, L., Quinlan, A, and Ryan, P. 2018. Wayfinder: a resilience guide for navigating towards sustainable futures. GRAID program, Stockholm Resilience Center. www.wayfinder.earth).

We have used these techniques to obtain input from our stakeholders to ensure that our modeling scenarios align with outcomes they would like to see in the future. At our annual meeting in spring 2018, we asked our Stakeholder Advisory Group (SAG) members to discuss:

- 1) Their current FEW management priorities,
- 2) What each saw as desired management states for their organization, and
- 3) How innovations in their sector(s) are, or could be, shaping the way they manage resources.

Despite their different missions and sectoral foci, there were many common challenges. All SAG members agreed that their organizations were interested in long-term (e.g., decadal) planning. The need to understand how resource availability may change in the future, and how those changes will impact their end users, is a top priority. Yet the information needed to plan and make long-term decisions is often accompanied by a high degree of scientific uncertainty. Managing with precision to achieve reliability and predictability goals becomes difficult when faced with greater scientific uncertainty. And, while many stakeholders indicate that their organization's ultimate goal is to strive for adaptability and flexibility, a lack of concrete information from which to make optimal decisions can be extremely limiting.

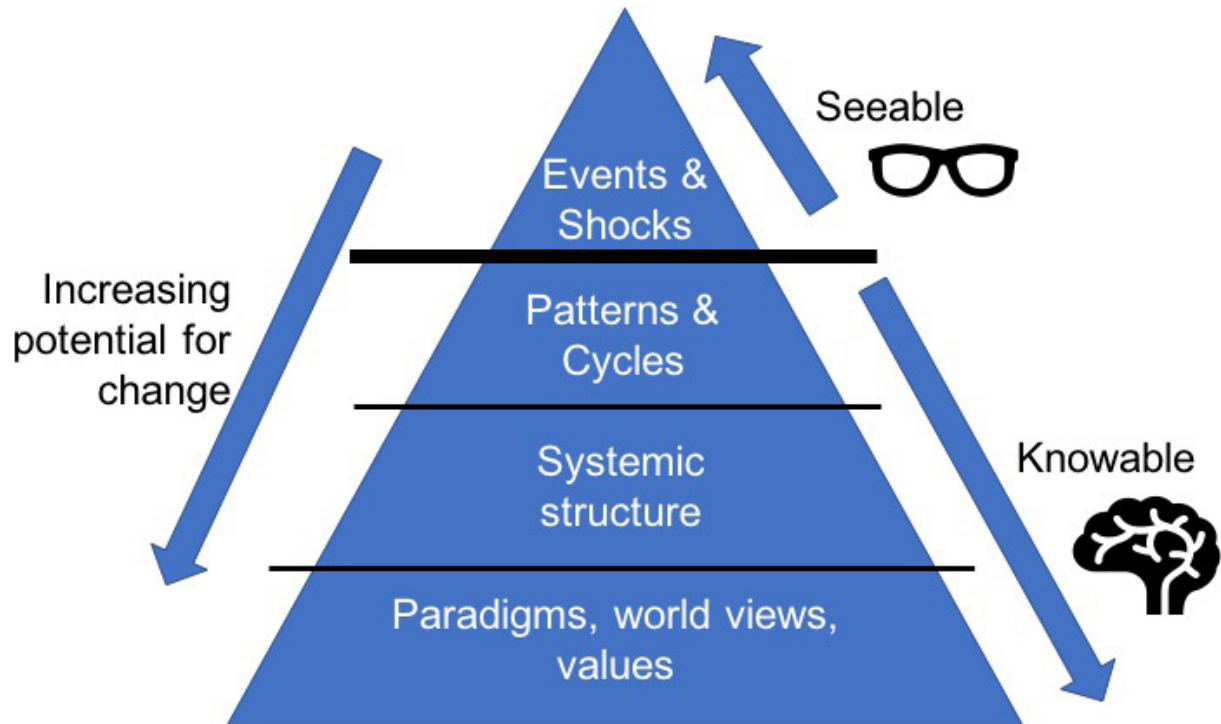


Figure 3. Framework for characterizing a system in a resilience assessment. Participants need to identify not only the obvious problems driving the need for the assessment, but the underlying structure and paradigms that shape how the system will respond to change (adapted from Enfors-Kautsky, E., Järnberg, L., Quinlan, A, and Ryan, P. 2018. *Wayfinder: a resilience guide for navigating towards sustainable futures*. GRAID program, Stockholm Resilience Center. www.wayfinder.earth).

When asked to define their “ideal future” for the Columbia River Basin, those in the food sector discussed the importance of successful management of food safety and water quality, farming viability, and improved soil and water conservation. Those in the energy sector emphasized investing in a smart grid and meters, reducing energy costs and the dependence on fossil fuels, and creating better plans for integrated energy storage. Participants from the water sector focused on creating a healthy environment for fish, maximizing irrigation efficiency and minimizing water quality issues, ensuring groundwater availability, and developing more flexible water management policies. Collectively, they emphasized the need for increased communication across sectors, and policies that were informed by science. They also focused heavily on improving predictability and reducing uncertainty for decision-makers, and the importance of adaptive management and regional communication in managing within and between sectors.

The Columbia FEW team has used this input to build out the details of the conceptual model of the Columbia FEW system (see Padowski et al.’s conceptual mapping article), help guide data collection efforts, and develop the STAR Calculator (see Richey et al.’s article) and future scenarios to evaluate. We anticipate continuing to use the strategies we learned in the resilience workshop to ensure our tools and products provide meaningful insights to those managing food, energy and water in the Columbia River Basin.

An Integrated Tool to Assess the Sustainability and Resilience of a Food-Energy-Water System

Sasha Richey, Julie C. Padowski, Dustin McLarty, Fabio V. Scarpore, Jennifer E. Givens, Kirti Rajagopalan, Sonia A. Hall, Georgine G. Yorgey, Michael Briscoe and Jennifer C. Adam

THE STAR CALCULATOR IS BEING DEVELOPED TO QUANTITATIVELY COMPARE THE LEVEL OF SUSTAINABILITY AND RESILIENCE OF A FOOD-ENERGY-WATER SYSTEM UNDER DIFFERENT CONDITIONS, AND WILL ALLOW US TO EVALUATE HOW DIFFERENT TECHNOLOGICAL AND INSTITUTIONAL INNOVATIONS—ADVANCED GREENHOUSES, ENERGY DEMAND RESPONSE, MANAGED AQUIFER RECHARGE, WATER MARKETS—WOULD AFFECT THE SUSTAINABILITY AND RESILIENCE OF THE COLUMBIA RIVER BASIN.



One of the primary goals of the Columbia FEW project is to evaluate how different technological or institutional innovations (e.g., advanced greenhouses, energy demand response, managed aquifer recharge, water markets) impact the sustainability and resilience of the Columbia River Basin's food-energy-water (FEW) system. We are developing the Sustainability And Resilience (STAR) Calculator, a method to quantitatively evaluate the impact of novel or desired innovations within the FEW system, as well as the direct and indirect impact of different climate change scenarios in the Columbia River Basin.

The STAR Calculator produces a STAR value for each of the three sectors—food, energy, and water—based on quantitative performance indicators (*PI*) for that sector, weighted by how important that performance indicator is to the sustainability and resilience of the sector (Equation 1). The weighting factors (*WF*) that capture that importance sum to one, and are derived from expert opinion via the House of Quality approach described below. In the Columbia FEW project, the performance indicators will mostly be assessed using model output from the project's modeling efforts.

$$STAR\ Value_{FEW\ Sector} = \frac{WF_1 PI_1 + \dots + WF_n PI_n}{\sum_{i=1}^n WF_i} \quad \text{Equation (1)}$$

There is no upper limit to what the STAR Value can be, so the Value is not meaningful on its own and out of context. Its meaning arises when the Calculator is used to compare different scenarios. For example, how does the sustainability and resilience of the food sector change under a future climate scenario, with and without greenhouses becoming a common production practice in the future? A baseline scenario of historical conditions will serve as the reference point to compare future scenarios to *status quo*.

We have identified a set of approximately 10 performance indicators for each of the FEW sectors (Table 1). The indicators are metrics that measure social, environmental, and economic aspects of each FEW sector. Collectively, they measure the level of sustainability and resilience in the FEW system. But how to develop the weighting factors that quantify the importance of each indicator for sustainability and resilience? The default approach is to consider

each weight to be equal. However, this is not always appropriate, as some aspects of the FEW system may be more important than others to overall resilience and sustainability. We therefore adopted the House of Quality concept (<https://www.whatissixsigma.net/house-of-quality-qfd>), used in industry to convert customer preferences to engineering specifications, to determine the weighting factors for the STAR Calculator.

Table 1. Performance indicator for each FEW sector.

FEW SECTOR	Performance Indicators
FOOD	Food production per resource input (e.g. water, fertilizer)
	% of cultivated land in food vs biofuels
	Crop quality
	Import/export of food
	Size of farm operation
	Soil quality
	Jobs in agricultural sector
	Food storage
	Magnitude/frequency of curtailment
ENERGY	Average transmission system capacity factor (kWh transmitted/max carrying capacity)
	Average generation system capacity factor (kWh generated/rated generation capacity)
	CO ₂ intensity of energy delivered (ton CO ₂ / MWh)
	Hours of interrupted service (average customer hours per year)
	Smart meter installations (% of commercial and % of residential)
	Inter-regional transmission connection capacity
	Energy storage and demand response capacity (MWh and MW)
	Cost of delivered electricity (\$/MWh)
	Incentive or feed-in tariff for renewables (\$/MWh)
	Potential for wind/solar near population/industry centers (TBD)
	Average transmission system capacity factor (kWh transmitted/max carrying capacity)
	Average generation system capacity factor (kWh generated/rated generation capacity)
	Jobs in energy sector
WATER	Ratio of green to blue water use
	Reservoir storage capacity/annual river runoff
	Percentage junior water rights holders
	Exceedance of water quality targets
	Water use vs. availability
	Standardized precipitation index
	Streamflow exceedance probabilities
	Compliance with metering regulations
	Dollar amount of funds to support water systems
	Jobs in water sector
	Magnitude/frequency of curtailment
	Volume of unaccounted for water (e.g. losses)
	Diversity of water supply portfolio
	Financial health

Within a product development or manufacturing context, the House of Quality concept starts with a sample of customers who would be asked to weight the importance of different product features, for example, on a scale of 0-9. The relationship between these product features and the engineering specifications required to produce such features is then evaluated on a similar numeric scale. The House of Quality is then used to combine the customer preferences with the engineering needs in order to prioritize the development of certain product components over others. In the Columbia FEW application, the performance indicators are analogous to the engineering specifications. We identified and defined a set of “management targets” that are analogous to the product features (Table 2).

Table 2. Management targets to represent sustainability and resilience goals.

Management Target	Definition
Efficiency	The amount of output for a unit of input
Utilization	The extent to which the managed component of a system is being used at any given time
Capture	Natural resource use versus sustainable availability
Penetration	The percent to which best practices are implemented
Vulnerability	Whether or not the impact of disruption be mitigated with diversity/storage/flexibility
Reliability	Measurable disruption of the output of a sector (e.g., can the system deliver what it is intended to deliver)
Adaptability	Capacity and flexibility in responding to change
Viability	Ability to meet a certain goal or outcome without adaptation

The management targets are considered to be the goals that support a sustainable and resilient system. We will conduct a survey of diverse stakeholders from each FEW sector and our project team, asking them to rate the importance of each management target in their respective sector (called “importance factors,” Figure 1). The stakeholders and project team will also rate the level to which each performance indicator informs each management target (“interaction factors,” Figure 1) and is connected to the other FEW sectors (“FEW connectivity factors,” Figure 1).

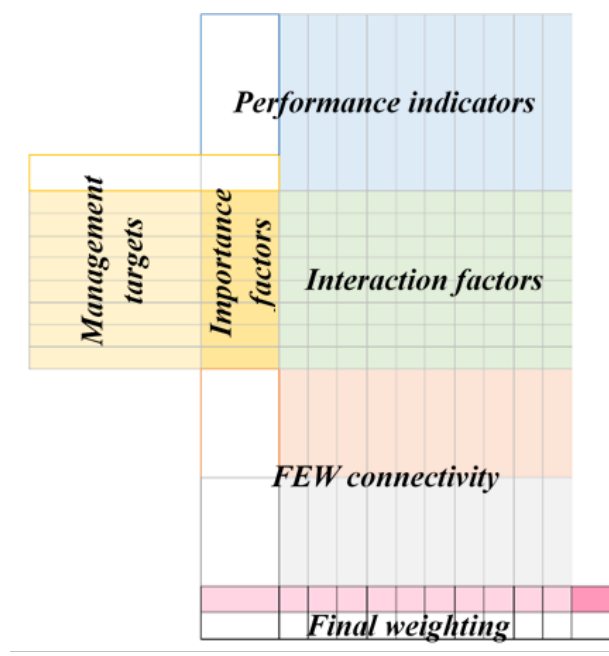


Figure 1. Simplified House of Quality diagram used to produce weighting factors for the STAR Calculator.

These rating scores will then be combined for each indicator into a final weighting factor (WF in Equation 1). The values of performance indicators under a particular scenario and these weighting factors will allow us to calculate a final STAR Value for each scenario of interest (Equation 1).

For example, a common indicator relevant to the “adaptability” management target across all three FEW sectors is “workforce employed by the sector.” The “interaction factor” between this indicator and “adaptability” would be high. This indicator incorporates economic and social aspects of sustainability by evaluating the extent to which each FEW sector supports livelihoods. “Water use divided by water availability” is an indicator that represents an environmental aspect of the water sector related to the “capture” management target. While the Columbia FEW team selected the initial set of performance indicators, the Calculator framework is flexible, and additional or different indicators could be incorporated to best fit the system under consideration.

By comparing the STAR Values of each FEW sector under different future scenarios or when modeling particular innovations we will be able to understand and quantify how different management actions affect both an individual sector, and the FEW system as a whole. This tool will make it possible to evaluate the impact of the trade-offs and other complex interactions that human and biophysical changes introduce within and between the food, energy, and water sectors. The STAR Values will provide valuable information to inform managers who aspire to coordinate decision-making among the FEW sectors to enhance the sustainability and resilience of the Columbia River Basin, or any other FEW system that adopts the STAR Calculator.

Looking Forward: Incorporating Feedback into the Columbia Food-Energy-Water Project

Georgine G. Yorgey, Sonia A. Hall, Jennifer C. Adam, Julie C. Padowski, Jennifer E. Givens, Michael Briscoe, Sasha Richey, and Fabio Scarpore

The Columbia FEW project's annual team meeting in September 2019 offered an opportunity for team members and our external advisory group to interact in person, helping catalyze and prioritize work that will continue through the end of the Columbia FEW project, and will inform future interdisciplinary work. The Columbia FEW team and our Advisory Group, which included representatives from municipal and energy public utilities, federal and state agencies, and private entities (Box 1), discussed three major topics:

- Key scenarios for focusing the integrated modeling work of the Columbia FEW project.
- The STAR Calculator, our integrated tool to assess the sustainability and resilience of the Columbia River Basin food-energy-water system.
- Perspectives on resilience, and how the concept is applied in academic and non-academic contexts.

Box 1: Advisory Group Entities Represented in the Columbia FEW Annual Meeting, September 10, 2019

Seattle Public Utilities
Chelan Public Utility District
Avista Corp.
Palouse Conservation District
US Geological Survey
Washington Department of Ecology – Water Resources
Mazza Research Organization Communication
Washington Department of Agriculture
Washington State Conservation Commission
US Bureau of Reclamation

Scenarios

The articles in Sections 2 and 3 of this Progress Report—*How Are the Food, Energy, and Water Sectors Expected to Change in the Future?* and *Key Innovations that Could Resolve Friction Points Between Food, Energy and Water Now and in the Future*—described the Columbia FEW team's work on an array of future scenarios of change that might play out in the region. We discussed these scenarios, as well as other scenarios of interest to researchers and stakeholders that the team could potentially incorporate into the existing modeling efforts. Advisors and team members then voted on priority scenarios they thought the team should tackle moving forward. The effort confirmed a high priority in a number of areas where the team is *already* working, including managed aquifer recharge, land use and land cover change, irrigation efficiency, and increasing wind and solar renewable energy (Table 1). The effort also identified some priority areas where the team is not currently focused, including multi-year droughts and heat waves. Following this insight, the team has been discussing whether this could catalyze future research in this area.

Table 1. Scenarios selected multiple times as priorities for the project. Scenarios in bold represent new scenarios that the Columbia FEW team is not working on. Those with an asterisk () are part of an independent project, Technology for Trade (see Yorgey et al.'s article for details).*

Scenarios
Remote sensing of evapotranspiration*
Energy demand shaping
Aquifer recharge
Multi-year water storage
Water markets*
Increasing renewables (with robust integration with the grid)
Irrigation efficiency
Multi-year drought
Policy changes
Extreme weather events (e.g., heat waves)
Decadal-scale impacts
Land use/land cover change

STAR Calculator

The group that has been working on the STAR Calculator presented new developments to this evolving framework that will allow quantitative comparisons of the level of sustainability and resilience of the food-energy-water system under different conditions (see Richey et al.'s article for an overview). The STAR Calculator relies on input from experts and managers of FEW resources to evaluate the level of importance different management targets (e.g., efficiency, reliability, vulnerability) hold, and how strongly they relate to various measurable metrics (i.e. performance indicators) that represent the health and resilience of the FEW system (e.g. food production per resource unit, energy storage and demand response, frequency of curtailment of irrigation). Our conversations at the annual meeting focused on gathering individual feedback from both team members not part of the STAR Calculator group and our advisors about the draft food, energy and water management targets and performance indicators that the team had developed (Figure 1). We then had a group discussion highlighting some of this feedback.



Figure 1. The Columbia FEW research team and Advisory Group members complete a survey as they provide individual feedback on the STAR Calculator management targets and performance indicators.

An initial review of the individual feedback suggests that ongoing development of the management targets should focus on reducing redundancy and more closely aligning them with the full team's definitions of sustainability and resilience. Key points that the advisors highlighted during the discussion included the need to more explicitly represent social, economic, and ecosystem indicators and to differentiate between indicators that represent an input to versus output from the system. Based on this discussion, the feedback provided in the survey exercise, and with iterative team discussion as necessary, we will continue to revise the management targets and performance indicators. Meanwhile, we are also continuing conversations with the team about the potential to integrate the STAR Calculator with modeling efforts. Once this work is complete, we anticipate that we will approach advisors again over the next year, asking them to provide weightings of the relative importance of the various management targets and performance indicators. We anticipate that the framework will be adaptable, for example, to other groups who may place different weights on the management targets.

Perspectives on sustainability and resilience

Both researchers and advisors participated in in-depth discussions of what sustainability and resilience means to them in the sector or sectors they work in, and how they are applied. A preliminary review of what we heard during these focus groups suggests that there are big differences but also overlaps in how researchers and practitioners define and apply these concepts. For example, several people expressed frustration over differing definitions. One person said, "When I was getting more acquainted with sustainability, to me, sustainability was like a buzz word. It was just something that has no meaning now. Sustaining what?" Another added, "I feel like I use a lot of different other [indices], instead of resilience and sustainability because ... everybody's understanding of those two are really different so we try to avoid using those". However, between researchers and advisors, similar definitions were also shared. An advisor explained the concepts, "sustainability is - can you function as it's designed to function ... can you really do year in and year out what it's designed to do? And then resilience is can you take the impact of unexpected blows ...the high and low blows and bounce back." A researcher gave a similar definition, "I think about sustainability and resilience as different things ... I think of sustainability as the capacity for a society to function in perpetuity, grow and improve without depleting fundamental resources, natural, social, economic. I think about resilience as being the capacity of a system to respond, regenerate, recover from a shock or a long-term pressure." Jennifer Givens and Michael Briscoe will be working to more systematically analyze the results from these focus groups, to extract more specific insights related to these differences, which could then shape better communication of academic results regarding sustainability and resilience of the food-energy-water system in ways that are useful to decision-makers working in these different sectors. Furthermore, this allows us to think about not only the meaning of the terms, but to more deeply consider assumptions explicit in these meanings and to ask questions such as, "resilience and sustainability of what and for whom", and to consider social implications, trade-offs, and power dynamics of management decisions.

Helping bridge from theory to practice

As we described earlier in this Progress Report, the Columbia FEW project is considered “use-inspired basic research” (see Hall et al.’s article on bridging theory to practice). The discussions during meetings such as our recent annual meeting are key to helping the Columbia FEW team understand the concerns and priorities of decision-makers currently working in the food, energy, and water sectors in the Columbia River Basin. The insights the research team obtains from such in-person interactions not only inform immediate next steps on the current research—such as what scenarios to focus on, or how to share sustainability and resilience information so that it is relevant to practitioners in different sectors—but also lead to discussions around future research projects, whether use-inspired or applied. We therefore would like to extend our gratitude to our Advisory Group participants for their willingness to invest their time in providing these insights. We hope that this Progress Report, our future Columbia FEW project results and our future work provide useful and relevant information that directly support your thinking and efforts related to understanding how you might improve the sustainability and resilience of the Columbia River Basin’s food-energy-water system, while achieving your entity’s specific goals and objectives.

6: Columbia River FEW Team and Authors

About the Authors



Jennifer C. Adam, Ph.D., is Associate Professor of the Department of Civil and Environmental Engineering at Washington State University.



Paris Edwards is a recent Ph.D. graduate in Water Resources Policy, Management and Law from the University of Idaho, Water Resources IGERT Program.



Muhammad Barik, Ph.D., is an Associate Scientist with the Universities Space Research Association/Science and Technology Institute (USRA/STI) at NASA's Marshall Space Flight Center.



Jennifer E. Givens, Ph.D., is an Assistant Professor with the Department of Sociology, Social Work and Anthropology at Utah State University.



Jan Boll, Ph.D., is Professor of the Department of Civil and Environmental Engineering and Interim Director of the Center for Environmental Research, Education and Outreach (CEREO) at Washington State University.



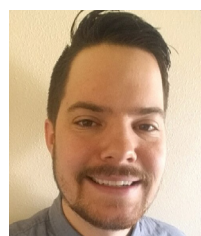
Michael Goldsby, Ph.D., is Associate Professor of Philosophy with the School of Politics, Philosophy, and Public Affairs at Washington State University.



Michael P. Brady, Ph.D., is an Assistant Professor and Extension Economist with the School of Economic Sciences at Washington State University.



Sammi (Samantha) Grieger is an M.S. graduate student in Environmental Science at Washington State University, Vancouver.



Michael D. Briscoe, Ph.D. candidate, is a Presidential Doctoral Research Fellow in the Department of Sociology, Social Work, and Anthropology at Utah State University.



Christian D. Guzman, Ph.D., is an Assistant Professor of Civil and Environmental Engineering at University of Massachusetts Amherst, and formerly a Postdoctoral Fellow in Civil and Environmental Engineering at Washington State University.



Barbara Cosens, M.S., J.D., LL.M., is a University Distinguished Professor with the University of Idaho's College of Law and its Water Resources Program.



Sonia A. Hall, Ph.D., is a Sustainable Systems Analyst with the Center for Sustaining Agriculture and Natural Resources at Washington State University.



Stephanie Hampton, Ph.D., is a Professor in the School of the Environment at Washington State University, and is currently serving as Division Director of Environmental Biology at the National Science Foundation.



Moses Luri is a Ph.D. graduate student with the School of Economic Sciences at Washington State University.



John Harrison, Ph.D., is the Edward R. Meyer Distinguished Professor with the School of the Environment at Washington State University, Vancouver.



Keyvan Malek, Ph.D., is a Postdoctoral Associate with the Department of Civil and Environmental Engineering at Cornell University.



Season Hoard, Ph.D., is an Assistant Professor with the Division of Governmental Studies and Services and the School of Politics, Philosophy and Public Affairs at Washington State University.



Fidel Maureira is a Ph.D. graduate student with the Department of Biological Systems Engineering at Washington State University.



Maoyi Huang is an Earth Systems Analysis and Modeling Earth Scientist at the Pacific Northwest National Laboratory (PNNL).



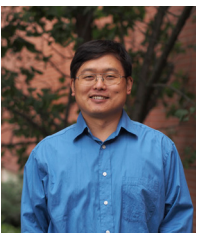
Dustin McLarty, Ph.D., is an Assistant Professor with the School of Mechanical and Materials Engineering at Washington State University.



Se-Yeun Lee, Ph.D., is an Instructor in Civil and Environmental Engineering at Seattle University.



Ashley Mills is a Ph.D. graduate student with the Clean Energy Systems Integration Lab at Washington State University.



Mingliang Liu, Ph.D., is an Assistant Research Professor with the Department of Civil and Environmental Engineering at Washington State University.



Daniel Mueller, Ph.D., is an Associate Lecturer of Political Science at the University of Wisconsin - La Crosse, and formerly a Research Assistant with the Division of Governmental Studies and Services at Washington State University.



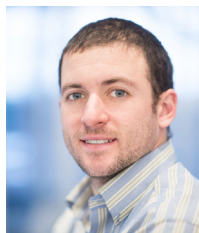
Bradley Luff, B.S., is a M.S. graduate student in the School of the Environment at Washington State University.



Julie C. Padowski, Ph.D., is the Assistant Director of the Center for Environmental Research, Education, and Outreach (CEREO), Washington State University, and a Clinical Assistant Professor with the State of Washington Water Research Center.



Nigel Pickering, Ph.D., is a Research Associate Professor at the Washington Stormwater Center, and affiliate faculty with the Department of Civil and Environmental Engineering, Washington State University.



Adam Wicks-Arshack, J.D., is a Ph.D. candidate in the Water Resources Graduate Program at the University of Idaho.



Kirti Rajagopalan, Ph.D., is an Assistant Research Professor with the Center for Sustaining Agriculture and Natural Resources at Washington State University.



Jonathan Yoder, Ph.D., Economics Professor with the School of Economic Sciences at Washington State University, and Director of the State of Washington Water Research Center.



Sasha Richey, Ph.D., is an Assistant Professor with the Department of Civil and Environmental Engineering at Washington State University.



Georgine G. Yorgey, M.P.A, is the Associate Director of the Center for Sustaining Agriculture and Natural Resources at Washington State University.



Begum Rabeya Rushi, M.S., is an associate engineer for the City of Hutto, Texas.



Richael K. Young, M.S., is co-founder and Chief Executive Officer of Mammoth Trading.



Fabio Vale Scarpore, Agronomist, Ph.D., is a Postdoctoral Researcher with the Department of Civil and Environmental Engineering at Washington State University.



Matthew Allen Yourek, M.S., is a Ph.D. student with the Department of Civil and Environmental Engineering at Washington State University.



Claudio Stöckle, Ph.D., is a Professor with the Department of Biological Systems Engineering at Washington State University.



Mengqi Zhao, Ph.D. candidate, is a Research Assistant with the Department of Civil and Environmental Engineering at Washington State University.

Additional Columbia FEW team members that contributed to the work
described in this Progress Report:

Liz Allen, Collins Kissi Asante-Sasu, Mike Barber, Courtney Cooper, Randy Fortenbery, Ames Fowler,
Alex Fremier, Tina Karimi, Steve Katz, Ian Kraucunas, Chad Kruger, Michael Meyer, Roger Nelson,
Hasan Roshan, Brooke Saari, Nathalie Voisin, Becky Witinok-Huber



Suggested Citation:

Hall, S.A., Yorgey, G.G., Padowski, J.C., Adam, J.C. 2019. Food-Energy-Water: Innovations in Storage
for Resilience in the Columbia River Basin. Progress Report for the Columbia River FEW Project.
Available online at www.fewstorage.wsu.edu

FOOD - ENERGY - WATER

