Clackamas Watershed Resilience

Phase I Report

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PORTLAND STATE UNIVERSITY

The Institute for Sustainable Solutions works to match the passion and expertise of Portland State University faculty and students with the experience and needs of community groups, government agencies, and businesses to develop practical solutions for more equitable, livable, sustainable cities and regions.

Clackamas River Water Providers

The Clackamas River Water Providers is a coalition of the municipal water providers that get their drinking water from the Clackamas river who are working together on water resource issues.

Water Environment Services

The Water Environment Services partnership provides surface water management and sanitary sewer service for more than 165,000 customers in Happy Valley, Milwaukie, Gladstone, Oregon City, West Linn, Johnson City, Hoodland, Boring, Fischer's Forest Park and unincorporated Clackamas County.

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Clackamas Watershed Resilience Project

Phase I report

Executive Summary

Introduction

The Clackamas River provides drinking water to over 300,000 people in Clackamas and Washington Counties, as well as recreation opportunities, and irrigation for farms. Like other areas of the Pacific Northwest, the Clackamas River Watershed (CW) is vulnerable to changes in climate that could impact water supplies and the natural and human systems that depend on them. Increases in winter flow and decreases in summer flow are particularly likely to have negative impacts on water resources and water-dependent industries and ecosystems.

Increased frequency of high-impact atmospheric river rainfall events, coupled with sea-level rise effects on the mainstem Willamette River are an increased threat to the resiliency of the wastewater and stormwater infrastructure in the CW. Increased stormwater runoff may also add more non-point source pollutants to the Clackamas River, and hotter, drier summers could lead to increased water demands and mean more forest fires that have compounding impacts on water quantity and quality.

The extent to which Clackamas water resources provided by the watershed are susceptible to impacts from climate change into the mid and late 21st century is unknown. Previous research shows that streamflow in the CW is more sensitive to changes in temperature than to changes in precipitation (Graves and Chang 2007, Jung et al. 2012). A holistic understanding of recent and historical trends in climate, hydrology, and management of the CW can help water and land

Project Goal

The goal of the Clackamas Watershed Resilience project is to help project partners understand local impacts of climate change on water quality and quantity in the region; and develop strategies to sustain a healthy, reliable water source.

Project Team

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managers in preparing for and responding to changing human and natural conditions. This report describes the first phase of a multi-phase applied research project developed in partnership between Portland State University (PSU) and partners at the Clackamas River Water Providers (CRWP) and Water Environment Services (WES) of Clackamas County to inform stakeholder understanding of the Clackamas River Watershed resilience to climate variability and change.

CRWP represents 8 water providers on matters of collective interest including watershed protection and education. Many of the same communities are provided sanitary sewer and stormwater management services in the urbanized areas of North Clackamas County by WES. WES provides wholesale sanitary sewer service to the cities of West Linn, Gladstone, Oregon City, Johnson City, and Milwaukie. Stormwater management service, in addition to sanitary sewer service, is provided to the City of Happy Valley, as well as a large urbanized unincorporated area of Clackamas County.

The outcomes of the proposed project will equip the CRWP, WES, and other stakeholders in the CW with the foundations for developing a resilience plan by identifying strategies that make the CW less susceptible to disturbance events or that promote quick system recovery following a disturbance. Adaptation strategies may include tactics that address the built environment, water infrastructure, green infrastructure, ecosystem services, riparian buffers, flood plain connectivity, land use planning, alternative water sources, and collaboration across stakeholders in each of these areas.

Project Team Process and Scope

This report describes research which was completed from March 2017-June 2018 focused on stakeholder interests in resilience, as well as historical changes in climate, hydrology, fire, and resource management in the CW. The objectives of the project were to: *(1) help clarify the extent to which the quantity, quality, and timing of water resources provided by the CW have changed in recent history and (2) build a framework for understanding how susceptible CW water resources are to the impacts from climate change into the mid and late 21st century.*

The findings described here detail some of the systems that drive water quantity and quality in the CW and will inform modeling exercises in the next phase of research which will consider climate change scenarios, future land uses, and adaptation strategies.

The Phase I project team included representatives from CRWP, WES, faculty and graduate students from Portland State University, and a project manager from the Institute for Sustainable Solutions. The project team met monthly to discuss research questions, share research updates and findings, and the implications of the results. Research focused on:

- **Stakeholder concerns:** In addition to primary project partners, CRWP and WES, the team interviewed fifteen additional governmental and non-governmental stakeholders in the CW to help understand the major areas of concern around water availability and quality (Chapter 1).
- **Local precipitation patterns:** The team focused on characterizing local precipitation patterns and changes in precipitation patterns from 1980 to 2016. Researchers described drivers of

extreme precipitation events that could impact water quality, flooding, and snow pack (Chapter 2).

- **Turbidity:** The team studied the drivers of turbidity to better understand how water quality may be impacted by changes in precipitation as well as land uses (Chapter 3).
- **Flow patterns and flood:** The team looked at historic flow patterns to understand the influence of snowmelt and extreme precipitation on flow, as well as the risk of flooding as a result of seasonal changes in flow and sea level rise (Chapter 4).
- **Fire risk:** The team considered what climate factors drive wildfire risks in the CW and studied patterns surrounding historic wildfires (Chapter 5).

Clackamas River Watershed Resilience Project Key Findings

Following are some of the key findings from the first phase of work. A more detailed explanation of these findings is included in the larger report.

1. Stakeholders are interested in more engagement around climate resilience and adaptation strategies. Locally relevant scientific information is needed to help facilitate further stakeholder engagement on resilience. Major areas concern for stakeholders include: development and planning in the urbanizing areas of the CW, pesticide and chemical use, wildfire risks to the CW, septic system failures, balancing water supply and consumption.
2. Precipitation has an impact on both water quantity and quality in the CW. The timing and amount of snow impacts water quantity, and extreme precipitation events have an impact on water quality. Observed trends do not show a significant change in annual precipitation (2015, a low precipitation year, was a major outlier); however, given the importance of the timing and frequency of extreme rainfall events (especially atmospheric rivers), it is important to continue monitoring precipitation patterns including seasonal change and snowmelt timing in the CW.
3. Water quality in the CW is affected by land uses. Observations of the timing of precipitation and turbidity across the CW suggest that urbanization impacts water quality by reducing the response time between precipitation and increased turbidity. Increased urbanization may have a more significant impact on water quality in the future if combined with increases in the frequency of extreme precipitation.
4. River flow appears to have shifted to a more rain-driven system, with greater winter flows and less snow-melt driven flows, following trends also observed in the Columbia River (Naik & Jay 2005). A shift to a larger winter hydrograph but less summertime flow could be a significant concern, if combined with warmer summers and larger summertime water demand (due to development) in the CW.
5. Wildfire in the CW is driven by high drought conditions observed up to one month before ignition usually in June and July, and the dryness of the atmosphere in the one to three days immediately preceding when fires ignite. The observations suggest that a humid august is an important control on fire activity, so the timing of precipitation and water availability are important in determining the future risks of wildfire.

Next Steps

This project will continue through June of 2020. The Phase II collaborative research team will continue to meet regularly, and focus on the larger project goal of help project partners understand local impacts of climate change on water quality and quantity in the region; and develop strategies to sustain a healthy, reliable water source. Phase II will integrate Phase I results into climate change scenarios, in order to provide more detailed feedback about predicted future changes in climate that will affect water resources. The team will also expand their focus to include strategy recommendations for CWP and WES by hosting workshops with stakeholders aimed at fostering dialogue around locally relevant scientific information on climate change and increasing the capacity to develop resilience and adaptation strategies in the CW.

Stakeholder engagement around water quality and quantity in the Clackamas River Watershed

Research Questions

The purpose of stakeholder engagement for this project was to help the project team and partners better understand *(1) what risks and vulnerabilities to water resources in the Clackamas River Watershed (CRW) are perceived by stakeholders, (2) what are the potential opportunities and barriers to adapting to current and future challenges, and (3) how much stakeholder engagement and political will exists to advance adaptation efforts.*

Research Approach

Erin Upton interviewed staff and representatives from CRW stakeholder agencies and organizations to better understand perceptions on the meaning and feasibility of adaptation and resilience to climate change in the CRW. Participants were selected with assistance from the project partners, the Clackamas River Water Providers and Clackamas County Water and Environment Services. Interviews were conducted in person, recorded, transcribed, and thematically coded using Atlas.ti software. Seventeen interviewees from 15 agencies/organizations included:

Federal government:
USFS Mount Hood National Forest, *District Ranger*

State government:
Department of Environmental Quality, *Basin Coordinator*
Oregon Department of Fish and Wildlife, *Fish Biologist*
Oregon Department of Agriculture, *Water Quality Specialist*

County government:
Water Environment Services, *Policy Analyst*
County Parks and Forest, *Parks & Forest Manager*
County Administration, *Assistant County Administrator*
Department of Planning, *Director of Planning*
County Disaster Management, *Director of Disaster Management*
Clackamas Soil and Water Conservation District, *General Manager, Riparian Specialist*

Municipal government
City of Happy Valley Planning Department, *Planning Services Manager*
Sunrise Water District (Happy Valley), *Engineer*

County-wide organizations
Clackamas River Water Providers, *Water Resource Manager*
Clackamas River Basin Council, *Executive Director*

Private
Portland General Electric, *Project Manager, Environmental Compliance and Licensing*

The interviews resulted in over 220 pages of transcripts, which were then coded[1] to allow the researchers to better understand, link, and make conclusions about the most important issues that stakeholders mentioned in the interviews. The transcripts were coded using the following major categories: threats, stakeholders, and adaptation. Each category was then thematically broken into subcategories based on the content of the interviews (results specific to each subcategory listed above are presented as Appendix 1 to this report):

Threats

Water quality
Water quantity
Development/urbanization/population growth
Climate change
Others
A variety of "Keeps me up at night" scenarios

Stakeholders

Who is engaged
Who is missing
Political will
Messaging and outreach

Adaptation

Barriers
Opportunities
Appropriate scale

Findings

Several cross-cutting themes emerged from the stakeholder interviews related to our research questions about climate adaptation and resilience in the CRW. The findings reported below highlight the following four cross-cutting themes:

1. **Partnerships and engagement: stakeholders want more engagement around climate adaptation and water resource resilience planning for the CRW.**
2. **Development and climate change: stakeholders are concerned about increased development impacts in light of unknown future climate change impacts.**
3. **Increased education for elected officials: Stakeholders believe public and elected officials need more education about land use impacts on water resources.**
4. **Stakeholders need translated and relevant science to better inform management and policy decision-making.**

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[1] One transcript was coded by both Upton and Nielsen-Pincus and coding results were discussed to ensure reliability of interpretations. Upton coded the transcripts from the remaining 16 interviews

Our interview guide asked a variety of questions about the threats and vulnerabilities to water resources in the CRW in the context of climate change, who is championing these four themes, and how capable we are of overcoming them. Participants noted a wide array of threats and vulnerabilities at the nexus of water resource management and climate change, which were generally organized along the lines of water quality and water quantity; thematic results are described in Appendix 1. The following results highlight some of the cross-cutting themes we observed from synthesizing the interview conversations. Many of the thematic topics highlighted by interviewees were similar to those envisioned by the original ISS sponsored research team. The interviews helped confirm the validity of research questions posed by the broader ISS team, identified a network of individuals interested in these topics, and illustrated some ideas on how stakeholders in the CRW can overcome barriers to managing future uncertainties.

1. Partnerships and engagement

"…if you think of the threats to water, there's a lot more coordination that could be done in terms of the science and its application… [to] address the uncertainties and the realities of land management."

The most commonly mentioned opportunity to address threats to the CRW's water quality and water quantity was to increase and enhance partnerships related to watershed resource management. Beyond the threat of climate change, stakeholders discussed the importance of resilience planning across jurisdictions and organizations to address the array of potential threats to water resources in the CRW. As one participant stated in relation to the need for increased engagement: "Everybody is just spread too thin, but I think the opportunity and the benefit [effective partnerships] create would overwhelm that." Some participants pointed to the importance of existing multiple stakeholder partnerships, like the Clackamas Stewardship Partners and the Clackamas River Water Providers, which already look at the CRW more holistically. Participants indicated that these types of partnerships could help participating agencies and organizations to think more strategically about resources, priorities, and coordinated planning. One participant said, these types of partnerships "break down the silos and apply knowledge or research…" from one arena to the broader effort. In addition to highlighting existing partnerships, participants pointed towards future opportunities. For example, one participant indicated how a cross-departmental Clackamas County climate action plan would allow more integrated planning, while also linking to state and international climate goals. Another noted opportunity was Clackamas County's biennial hazard assessments, which could integrate climate adaptation and resilience planning if hazard assessments were to identify climate related hazards and risks. As a partnership engagement opportunity, hazard assessments bring many stakeholders together, including representatives from water providers, fire, law, public health, social services and others. Participants noted both the opportunity and the challenge of facilitating these efforts. "Time is stretched too thin" said one participant, and "We do so much communication now via email and phone" that there are limits to the benefits they could get from "sitting down and talking through the issues". Any additional effort to bring stakeholders together around these issues will need to be time and resource efficient to ensure a worthwhile effort.

2. Development and climate change:

"Just plain old development and the various people and entities that are involved that aren't necessarily coordinating on long-term planning and longer term hydrologic impacts of development."

The urbanized areas of the watershed are growing in population. Much of the area slated to be developed under the Portland Metropolitan region's existing urban growth boundary and areas considered suitable for future development (urban reserves) are in the CRW. Population growth and development will have a number of impacts on the watershed and participants repeatedly brought these issues to the front of our conversations about climate change. As one participant expressed: "You can't just keep adding tens of thousands of people a year into a basin and not have it have some effect."

Participants identified concerns about increased impervious surfaces, and limitations for wastewater and drinking water infrastructure, in addition to recreational overuse of the river and forests in the upper watershed. First, many participants noted that increased development typically results in more impervious surfaces that contribute to more "flashy" hydrologic events that increase pollutant loading and turbidity in the Clackamas River. Development can also threaten floodplain connectivity, further limiting the capacity of the hydrologic system to absorb rainfall events. Additionally, some participants indicated that current wastewater infrastructure cannot handle increased development in all service areas, and will result in an increase in the number of homes on septic systems. This rural growth presents further risks due to the potential for individual septic system failures and related water contamination. Participants were particularly concerned about how potential impacts of development could become compounded by climate change.

Participants made the connection between development and climate change. Climate models indicated the potential for an increasing number of high impact rainfall events, which could further increase the pressure on wastewater infrastructure. Concerns also exist regarding drinking water shortages as demand rises with population growth, and climate change may affect the timing or the quantity of water produced by the CRW. Finally, several participants also noted that an increasing population also results in increasing recreation in the upper watershed. As some participants indicated the CRW is already "loved to death" and more people will further exacerbate that challenge.

As indicated above, many participants perceived climate change as a threat to the CRW due to a number of related factors. For example, some participants highlighted how changing and variable weather patterns would interact with population demands for services**.** Participants noted concern over longer, hotter, and drier summers; changes in the frequency and intensity of precipitation events, and reduced snow pack leading to earlier and lower low summer flows. Participants noted that the impacts of changing and variable weather patterns on management of the CRW could affect water availability for municipal use, irrigation, and fish habitat. Another common concern was over big storm events. Intense storms can cause bigger "first flush" events, washing pollutants from agricultural and urban areas into waterways resulting in increased disinfection bi-products in drinking water. One participant highlighted that current infrastructure struggles to handle "what is coming down the pike" … and "with more and more people moving here and more and more development in our service area combined with higher impact rainfall events, there's a lot of things that are coming at us…" Big storm events can also impact hydroelectric dam infrastructure. Other climate related concerns included (1) an increase in wildfire hazard due to less resilient forests that are more susceptible to pests and drought, (2) increased algae blooms that compromise drinking water due to declines in water quality, (3) poor ocean conditions further impacting anadromous fish runs in the Clackamas River, and (4) the risk of sea level rise increasing flood risk to low-lying wastewater infrastructure near the confluence of the Clackamas and Willamette Rivers.

3. Need for improved public and elected official education about land use impacts on water resources.

"Once we adopted our drinking water protection plan, it became clear very quickly that there's a huge outreach component in the watershed… We have two audiences. One [is] our customers, because it's their water dollars that are funding our programs upriver. And then our other audience is the people who are actually in the watershed, in that their land-use can impact our drinking water source."

Although interviewees readily identified an array of agencies and organizations that are championing ways to address the threats they perceived to the CRW (Table 1), participants elaborated in more depth about the need for improved education of the public and of elected officials. Specifically, many participants addressed links between land management and impacts on drinking water. Participants discussed the need for public messaging and education about pesticides, agricultural pollution, fire danger, waste management and dumping, septic system failures, and water consumption. As the population of the region continues to grow, participants stressed the need for ongoing public awareness, education, and outreach. Some organizations and programs in the CRW have outreach and education as a core part of their mission, including the Clackamas Soil and Water Conservation District, the Clackamas River Basin Council, and the Clackamas River Water Providers. As one participant noted, the challenge is about mobilizing the connection many people have to the Clackamas River: "How do you educate people better, [so they] know how to deal with the issues [i.e. threats]? We have a great opportunity, I think, in the Portland Metro Area to have a large volunteer base and a lot of people that are interested in seeing the river protected. They just don't know what to do."

In addition to public education, many participants also noted a need to educate elected officials about water management and long-term planning needs. Several participants noted how election results can lead to pendulum swings in political values that impact the CRW, and thus participants further stressed the need to continue to educate elected officials about vulnerabilities to water resources and planning and management necessities. Others noted that Oregon's nearly 50 year old system of land use planning has resulted in a more general acceptance of environmental regulations, but that development of new areas, like Happy Valley, create a desire for greater local control over utilities, parks, and other services that can impact the health of water resources. Many respondents also highlighted existing and anticipated reductions to federal and state government agency budgets. Oregon's tax system, noted one participant, results in public officials putting levies in front of voters to pay for the services of local government. This contributes to the need for education of both the public and elected officials if champions in the CRW want the political will to address the threats to water resource management from climate change or any other source.

One participant put the issue of political dynamics as a straightforward issue that predictably impacts water resource management. Utilities have city councils or elected boards that govern them and “you are constantly teaching your elected officials what you do and how you do it, and how we plan our master planning into the future, and how we outline the improvements we're going to make over time.” The participant went on to note that the discussions about water resource management eventually turn back to financial resources, and “what do you charge for system development charges as communities are growing. You get new people every year, you just have to continue [to] educate them.

Table 1. Organizational mentions of agents of water resource management in the Clackamas River Watershed (bold indicates interviewee organizations; numbers indicate the number of mentions across the 15 interviews.

Organizations	# of mentions
Local Government	
Clackamas Soil & Water Conservation District	10
Clackamas Water Environment Services	8
Metro	7
Clackamas County Planning	5
Clackamas County Sheriff	4
Clackamas County Parks and Forests	3
Clack County Road Maintenance	3
Clack County Administrators	2
Clackamas County Public Health	2
Clackamas Pesticide Program	2
Clackamas County Disaster Planning	1
Clack County Office of Sustainability	1
County Board of Commissioners	1
Clackamas County Social Services	1
Federal Government (16)	
US Forest Service - Mt Hood National Forest	
US Geological Service	6
Environmental Protection Agency	4
Natural Resource Conservation Service	2
National Weather Service	1
Federal Energy Regulatory Commission	1
US Forest Service - PNW Research Station	1
	1
Intergovernmental Agencies (19)	
Clackamas River Water Providers	6
Regional Water Consortium	4
Non-Governmental Organizations (42)	2
Oregon Association of Clean Water Agencies	1
PNW Clean Water Association	1
Universities (5)	
Oregon State University	2
Portland State University	2
North Willamette Extension Service	1
Non-Governmental Organizations (42)	
Clackamas River Basin Council	18
Clackamas Stewardship Partners	7
Clackamas River Enforcement & Ecology Workgroup	3
Rocky Mountain Elk Foundation	1
Oregon Hunters Association	1
Clackamas Partners	1
Friends of Trees	1
River Keepers	1
Arbor Day Foundation	1
Trout Unlimited	1
NW OR Jet Boaters Association	1
BARK	1
Oregon Environmental Council	1
Oregon Association of Soil and Water Conservation Districts	1
Oregon Wild	1
ENRGY Kayaking	1
Network of Oregon Watershed Councils	1
Private Sector Business Organizations (8)	
Portland General Electric	8
State Government (39)	
Oregon Dept of Environmental Quality	17
Oregon Dept of Fish and Wildlife	6
Oregon Dept of Agriculture	5
Oregon Dept of Water Resources	3
Oregon Watershed Enhancement Board	3
Oregon Health Authority	2
Oregon Dept of State Lands	2
Oregon Dept of Forestry	1

Other notable mentions included local cities (6), the timber industry (2), tribes (2), and the agricultural community (1), but did not identify specific organization.

4. Presenting translatable science to better inform management and policy decisions.

"Ideally if we had a better understanding in regards to climate change that might adapt some of the ways that we look at our water system planning in the future."

Uncertainty was a common refrain across interviews. For example, participants talked about floodplain and riparian area regulation. On one hand, there is resistance to enact new regulation that would protect floodplain functions, but on the other hand current litigation claims that the Federal Emergency Management Agency's flood insurance program is violating the Endangered Species Act, and could result in federally mandated floodplain protection at the potential expense of agricultural productivity or development. In another example, a participant noted that the county is currently developing a proposal for a county-wide surface water district to integrate planning and management around water in a comprehensive way, which could impact development rules. In addition, others discussed management uncertainty in the upper reaches of the watershed, where a Northwest Forest Plan revision could impact national forest management starting in 2020.

Multiple participants indicated that scientific research, including research conducted in this project, could contribute to an understanding of how robust different management approaches may be to uncertainties, including climate change, in the CRW. Several participants indicated that an adaptive management cycle could be beneficial, where managers and research collectively develop hypotheses about the effects of management approaches that are tested and used to restructure future management. One participant specifically discussed opportunities to connect research and management: "We coordinate [research], both internally and with external partners, but it seems like if you think of the threats to water, there's a lot more coordination that could be done in terms of the science and its [management] application." The participant went on to say, "…we are science-based organization, but I still think that there's probably more work that could address the uncertainties and the realities of land management." Uncertainties in the science and policy landscape of land management weren't the only issues with which participants grappled. Urban water use was another dimension of water resource management that one interviewee highlighted, "unless we can … get water use down, we are just going to have to have bigger [treatment] plants" with their associated costs and water demands. When asked about the capacity of stakeholders in the CRW to address the threats to and uncertainties associated with water resource management from climate change and other sources, a vision of the CRW as a model for sustainable water resource management emerged from several participants. As one stated, "I do think that an opportunity exists for research, and then promoting the Clackamas as a model, for how we're able to accommodate development and growth, while protecting a source of drinking water, and the natural resources."

Implications for Clackamas River Watershed Resilience Project

Our intention was to highlight the interests and concerns shared by some of the major stakeholders in water resource management for the CRW, as well as to provide context to the science conducted by the other research team members. The most compelling findings from our research have implications for managers and planners in the CRW. First, across a diversity of stakeholders there exists a desire for a larger scale resilience planning effort that integrates across municipal, development, agricultural, conservation, and water resource management interests to address the many uncertainties facing the CRW due to development, climate change, and other factors. A water resource climate adaptation or resilience planning effort may be an important tool for realizing that desire, mobilizing partnerships, and coordinating work that leads to more collaboration across jurisdictional and thematic boundaries. Second, we found that stakeholders had real substantive concerns about and could envision opportunities related to locally specific uncertainties in infrastructure and institutions managing water quantity and quality. This finding is important because university- and agency-based researchers in engineering, geography, and environmental sciences have both knowledge and methods for conducting research to understand these very types of uncertainties, and can produce information that may help inform decisions on these topics. Third, we found a common desire for more locally translated science that can be integrated into local policy and programs. This finding is particularly important for university- and agency-based researchers whose skills and knowledge could be incentivized to focus on locally-based applied challenges like climate adaptation and resilience planning. Beyond these broad implications, we also identified many more thematically specific findings (Appendix 1) that we hope provide ideas for management and research that directly address stakeholder concerns about the threats from climate change and other future uncertainties.

Next steps

Results from this research are intended to capture a current snapshot of the institutional landscape of managing current and future threats to water resources in the CRW. These results will be used to facilitate continued discussion about climate adaptation planning in the CRW and help foster dialogue between the scientific and policy/management communities. To further this research will require additional engagement with an even broader spectrum of stakeholders. We hope that this entry into understanding of the perceived risks and vulnerabilities, opportunities and barriers, and stakeholder engagement and political will to address climate change will foster that continued dialogue. For example, we would propose hosting a series of workshops in which we present findings from this project to different groups of stakeholders and discuss what actions best build on the assets within the watershed to address the vulnerabilities and risks faced by the watershed. These workshops would accomplish the dual goals of further facilitating dialogue and engagement among stakeholders and scientists, while also identifying development, land use, and water conservation strategies that are commonly supported across diverse perspectives. Outcomes would facilitate the development, communication, and implementation of science-based strategies for adapting to the impacts of climate change by developing strategies focused on expected threats to water quality and quantity, as well as new research efforts inspired by these workshops.

Characterizing Precipitation in the Clackamas River Watershed

Research Questions

The purpose of researching and describing precipitation in the Clackamas River Watershed is to better understand what key weather and climate features are important for water quality and quantity in the Clackamas River Watershed. Specifically we aimed to address the following question: *What are the climatological conditions that lead to the most impactful water quantity, quality, and management events?*

Research Approach

To answer the overarching research question, we focused on two key contributors to water quality and quantity: 1) Heavy precipitation and the associated storms that produce it and 2) Snow within the CRW, when and how much it accumulates, when and how quickly it melts, and how much liquid water is stored in the snowpack.

To investigate and characterize heavy precipitation and the associated storm systems that produce it, we focused on the large-scale weather patterns that have historically been linked to heavy precipitation events over the CRW. By large-scale weather patterns, we are referring to patterns on the order of 100s of miles which are characteristic of typical fall, winter, and spring storms in northwestern Oregon. The motivation for taking this approach is that heavy precipitation events can occur at very local scales, especially in the case of complex and influential topography such as in the CRW, and as a result these phenomena are difficult to resolve in state-of-the-art climate models which provide data pixels that are too coarse. Therefore, if we can understand the range of storm types that drive the local scale rain and snow extremes (storm types are large enough in scale for climate models to resolve them), we can use climate models to provide information on whether the types of storms that historically produced heavy precipitation are projected to change in the future.

Heavy precipitation over the CRW can occur with a variety of different weather patterns. In order to understand the full range of storm types/weather patterns that have resulted in heavy precipitation in the past several decades, we first identified days with extreme precipitation. We used the 90th percentile of 24-hour precipitation based on all days with measureable precipitation as the threshold to define a heavy precipitation day. We then identified the weather patterns on each of the days exceeding that threshold and used a machine learning approach called self-organizing maps to sort and summarize all of the weather patterns into 12 categories. This allowed us to make associations between different storm types (based on the 12 weather patterns) and heavy precipitation over the CRW. We then used an algorithm to determine which extreme precipitation days were associated with atmospheric rivers (narrow bands of high transport of water vapor in the atmosphere). Heavy precipitation analysis was performed over the years 1980-2016.

To investigate snowpack behavior in the CRW over the recent past, we analyzed snow water equivalent trends and climatology at two SNOTEL observation stations within the watershed. These two stations are Peavine Ridge and Clackamas Lake. Snow water equivalent is the amount of liquid water contained within the snowpack and is important for measuring the amount of water available for melt into the Clackamas River. We also focused on the 2014-2015 water year, which was characterized by an anomalous snow drought, to put this high impact year into perspective with recent and past observations. Snowpack analysis was performed over the years 1982-2016

Findings

Our research resulted in four key findings described below:

1. **Precipitation climatology**
2. **Atmospheric Rivers**
3. **Snowpack Trends**
4. **Winter 2015 in perspective**

1. Precipitation climatology

The CRW receives about 83% of its annual precipitation between October and April while extreme precipitation events account for 25% of all annual accumulated precipitation on average.

2. Atmospheric Rivers

Atmospheric rivers are key to the occurrence of heavy precipitation. They are present on 73% of heavy precipitation days and 42% of days with any measureable precipitation. Atmospheric rivers make up the largest proportion of heavy precipitation days during the fall (52%) and winter (49%). Furthermore, the geographic orientation of the atmospheric river is importation for determining whether the heaviest precipitation falls over the CRW or elsewhere. Because atmospheric rivers are very narrow bands of high water content in the lower levels of the atmosphere, the angle with which the atmospheric river impacts topography is important for how much rain or snow falls over the CRW. It is the lift of air provided by the mountains that causes the moisture in the atmospheric river to cool down and condense out as precipitation. If the atmospheric river intercepts the Cascades at a more perpendicular orientation, heavier rain or snow will fall than if it impacts the Cascades at a lower angle. The position and orientation of the atmospheric river is also important for determining whether most of the precipitation falls as rain or snow over the higher elevations of the CRW. More specifically, if the atmospheric river core is located a little to the north of the CRW, it is more likely that heavy precipitation will fall as rain, whereas if the atmospheric river is centered to the south of the CRW precipitation is more likely to fall as snow. This is because the atmospheric river itself is often associated with a surface front, which marks the boundary between cooler air from the north and warmer air from the south.

3. Snowpack trends

Since 1982, there has been a decreasing trend in the time from peak snow water equivalent to snow disappearance at Peavine Ridge. In other words, snowpack is melting faster today than it did in the past, however there is considerable year-to-year variability in the length of the snowpack season. This trend is statistically significant at Peavine Ridge only. Clackamas Lake does not exhibit a statistically significant trend. There is no statistically significant trend in April 1st snow water equivalent at either station. This all suggests that climate change has not had a major impact on snowpack in the CRW to date.

4. Winter 2015 in perspective

The winter of 2015 was a very unusual year regarding snowpack in the CRW, however 2015 did not stand out as particularly unusual as far as how low the peak snow water equivalent was observed for the season. This means that many years had similarly low peak snowpack as measured by the amount of water stored in the snowpack as 2015. 2015 stands out, however, as having an unusually low number of snow covered days. Clackamas Lake and Peavine Ridge had 63 and 60 days of snow cover respectively which is compared to a long term average of 160 days of snow cover. This was primarily due to an unusually large proportion of precipitation falling as rain instead of snow during Winter 2015. While future climate warming will likely lead to a shorter snow cover season and decreased spring snow water equivalent, 2015 was not consistent with recent observed trends and for the current climate should be viewed as an outlier. In other words, 2015 was not a "new normal," although it is likely that as warming continues into the mid-21st century, years like 2015 will start to become more common.

Implications for Clackamas River Watershed Resilience Project

This research focuses primarily on what happens to water before it enters the ground water and river system. By focusing on the meteorology that drives rainfall, snowfall, changes in water content within the snowpack, and the intensity of each of these, our research provides a foundation for a first order look at what climate change may mean for water quality and quantity in the CRW. Changes in the atmosphere will largely drive changes in other parameters that the other researchers are assessing making this research step critical for assessment of resiliency to future climate change impacts.

Next Steps

Future questions will focus on providing information about climate change and how it will affect water quality and quantity in the CRW in the coming decades. We will leverage our findings from the current research phase to drive our questions about future change. To answer questions about climate change we will use output from a large suite of climate model simulations that have been produced at modeling centers around the world and provided free to the research community via the web. All future information is therefore based on climate model "projections" and this is the term we will use to refer to future climate information.

1. Is there a projected change in the seasonality of heavy precipitation over the CRW?
2. Are the occurrence or seasonality of atmospheric rivers projected to change? Is the location and orientation of atmospheric rivers projected to change in relation to the CRW?
3. Are the weather patterns/storm types that have historically been associated with heavy precipitation events projected to change in frequency, orientation, or magnitude?
4. Can we project changes in freezing level over the CRW in a useful way, and if so, can we measure changes in the proportion of precipitation falling as rain versus snow over the CRW?
5. How is extreme heat projected to change over the CRW?

Drivers of Water Quality in the Clackamas River Watershed

Research Questions

Anticipated changes in extreme precipitation and streamflow patterns during rainy seasons under climate change may affect timing and magnitude of high turbidity occurrence—an indicator of water quality. An increase in turbidity level associated with projected climate change can threaten drinking water providers and increase the cost and difficulty to meet federal drinking water standards. In order to understand how turbidity might change as a result of changes in precipitation, we looked at what currently drive turbidity in the region. The questions we asked are: *(1) What is the observed trend and relationship between turbidity, discharge, and precipitation based on empirical data? (2) How does the timing of peak turbidity differ across the gauging stations and seasons? Does precipitation intensity impact the lag time between discharge and turbidity peak? (3) How closely is peak turbidity related to discharge and precipitation? Can we use the latter two to predict turbidity before a storm in a timely efficient manner? (4) How was turbidity affected by climate during a wet year (2017), a dry year (2015), and an average year (2013)?*

Research Approach

This study used a combination of literature review, construction of an empirical dataset, and historical trend statistical analysis to characterize the relationship between hydroclimate and water quality. The methods used to understand each research question are described below:

To describe the trend and relationship between turbidity, discharge and precipitation, we used data from three Clackamas River gauge stations. We characterized extreme precipitation events by discharge exceedance of over 20% of average monthly flow across three gauge stations on the Clackamas River. We focused on extreme precipitation events because they have historically been linked to elevated discharge and turbidity levels. We built a dataset composed of precipitation, streamflow, turbidity, and treatment plant intake water quality values and operation of treatment. Using this dataset, we conducted a series of statistical tests on a ten-year period from 2008-2017 and correlation between peak turbidity events and atmospheric river presence.

In order to understand more about what drives the timing of turbidity, we measured the lag between peak turbidity and peak discharge. The timing of turbidity peak events can vary by time and space. To examine whether land cover types and seasonality had impacts on timing and lag between peak turbidity and peak discharge, we used the National Land Cover Dataset to examine land cover type from a rural to urban gradient across three studied stations on the Clackamas River. We also divided our constructed dataset by early, mid, and late precipitation season to examine temporal variability. Lastly, the lag time between turbidity peak and discharge peaks was calculated and associated with precipitation patterns, because the timing of turbidity peaks can inform us about the proximity of sediments that are being eroded.

A correlation and regression model was used to examine the relationship between turbidity and discharge on multiple time scales, such as event, season, and year. Temporal dependence of elevated turbidity levels was closely examined to forecast event and seasonal forecast of turbidity exceedance, which can provide additional information for management and planning purposes for water treatment plants in the CRW.

Finally, we compared a wet and dry year turbidity trends. To examine vulnerabilities of the CRW to extreme events, we looked at annual precipitation and discharge average between 2008 and 2017 to determine the wettest, driest, and an average year. We then tried to relate the climatic conditions of these years to the turbidity behaviors that occurred in those years. The purpose of this research question is to show stakeholders that extremely wet and dry years caused by variability in climate change can greatly impact the frequency and magnitude of high turbidity levels.

Findings

Historical trends of Turbidity

The number of days in a year where the turbidity level exceeded 10 FNU at the NCCWC treatment plant intake is strongly associated with the number of days with intense precipitation (> 1 inch in 3 days) and annual average discharge. More than 80% of high turbidity events occurred between November and March in the past ten years. Elevated turbidity levels are strongly associated with increased discharge values. Approximately 60% of discharge and turbidity peaks dates fell within extreme precipitation events types which showed a high presence of atmospheric river events. This finding supports our expectation that atmospheric river occurrence in the Pacific Northwest is likely the cause of most extreme precipitation events and elevated levels of discharge and turbidity in the lower Clackamas River Watershed. Based on an observed relationship between streamflow, turbidity, and precipitation, we expect an increase in treatment system vulnerability to climate-related high turbidity events.

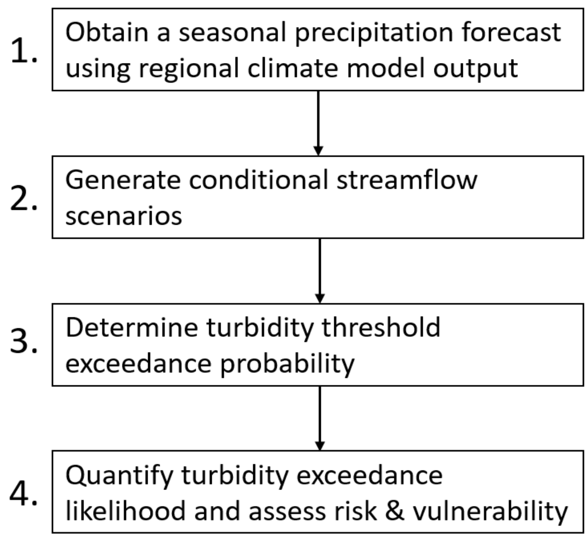
Timing of Peak Turbidity

We observed a pattern of turbidity peaking sooner before discharge during a storm event as the land cover gradient changes from forested/rural to urban area. Turbidity values tend to peak before discharge at Oregon City, while discharge peaks before turbidity for the same storm event. More impervious surfaces and developments near Oregon City are likely the cause of transporting sediments more quickly to water bodies. Estacada and Three Lynx are located farther upstream with more forested land cover and the additional of a few hydroelectric dams, which can slow down the transport of sediments during storms. However, results from our findings showed a few instances where the turbidity peak time and lag differ drastically in Oregon City, but we observed no statistically significant correlation with precipitation intensity or seasonality. We can conclude that in addition to meteorological drivers, landscapes and basin geomorphology plays a role in regulating sediment supply and turbidity levels as well, but not enough data (soil moisture) are available for further investigation. Urbanization is likely the cause of turbidity reaching peak values faster than discharge during storms in Oregon City. Installing additional turbidity and discharge monitoring between Oregon City and Estacada and tributaries along the Clackamas River may be useful in predicting turbidity values quicker prior or during a storm.

Turbidity prediction by precipitation and discharge

Although we have found a statistically significant positive correlation between event peak turbidity and peak discharge, the relationship is non-linear. Turbidity level increases exponentially with discharge, while discharge has a positive nonlinear correlation with cumulative precipitation. If we project extreme precipitation to occur at a higher magnitude in the Pacific Northwest, turbidity levels during these events may increase at a much faster rate than we expect. Early and late season precipitation events occurring in early winter, and late spring showed the strongest positive correlation to turbidity peaks. As seasonal climate forecasts become more accurate and able to calculate the probability of precipitation to be above-normal, near-normal, or below-normal, prospects of turbidity forecasts can be enhanced by seasonal precipitation forecast. Future investigation can consider calculating the turbidity exceedance likelihood based on streamflow scenarios and precipitation forecasts based on an approach used by Towler (2010) illustrated below.

Figure 1. Towler's Approach to Calculating Turbidity Exceedance



Sensitivity to extreme years

Using annual average discharge values, we identified the year 2015 to be representative of a typical dry year, 2017 as a typical wet year, and 2013 as a normal year. During the dry year annual average turbidity levels dropped as well as the number of days where turbidity exceeded 10 FNU at the NCCWS treatment plant. The year 2017 was an extremely wet year with 13 extreme precipitation events that had more than 20% exceedance of monthly average flow. We also saw a high number of days where turbidity exceeded 10 FNU at the water treatment plant, and a higher annual mean of daily turbidity maximum. 2015 is not a typical year, but it did not have a negative impact on turbidity levels, whereas 2017 as an extremely wet year that increased turbidity levels and lowered water quality in the winter season. If years like 2017 are becoming more common in the future, then we will expect more days when turbidity levels exceed 10 FNU, which can increase stress on drinking water treatments. Increased annual average air temperature did not contribute to turbidity peaks, but could cause more precipitation in the fall and winter to occur as rain instead of snow, which in turn increase flow. In addition, higher temperatures can also shift the timing of snowpack runoff to early spring, which can increase baseflow in spring and increase the likelihood of higher turbidity values during storms. This relationship has not been observed in the past, but can be highly possible if the Pacific Northwest experience more rapid air temperature rise.

Table 2. Annual average daily discharge and maximum turbidity in CRW, 2009-2017

	Estacada		Oregon City		NCCWC Turbidity	
Water Year	Annual Mean Discharge	Annual Mean of Daily Turbidity Max	Annual Mean Discharge	Annual Mean of Daily Turbidity Max	# of Days > 10 FNU	# of Storms Identified
2009	2727	7.64	3274	10.72	23	6
2010	2689	5.93	3113	5.05	14	6
2011	3360	6.23	4139	12.34	45	3
2012	3253	10.46	4159	13.56	28	8
2013	**2689**	**5.28**	**3305**	**6.17**	**15**	**8**
2014	2880	6.37	3525	6.58	26	11
2015	**2063**	**2.88**	**2483**	**4.95**	**11**	**5**
2016	2723	2.95	3460	6.44	16	6
2017	**3343**	**2.97**	**4394**	**7.41**	**30**	**13**

Implications for Clackamas River Watershed Resilience Project

Our findings could inform watershed managers and drinking water providers how best to manage lands and treatment plants during different storm events over time. Additionally, the results of other sections (e.g., changes in flow and fire activities) could have direct impact on the turbidity levels.

Next Steps

The second phase of the project will investigate the potential shifts in streamflow and sediment loads under different future climate projections in the 21st century. Together with the outputs of downscaled gridded climate data, we will run a process-based hydrologic model, SWAT (Soil-Water Assessment Tool) to simulate future changes in hydrology and water quality. Specific questions are as follows.

1. How will shifts in precipitation and temperature regimes impact seasonal discharge, turbidity, and summer stream temperature? What are the probabilities and range of these shifts? What combinations of hydro meteorological events (e.g., prolonged dry days followed by heavy rainfall events) are likely to induce high turbidity events?
2. What is the interannual variability of turbidity based on discharge? How does the relationship between discharge and turbidity vary between dry vs. wet vs. normal years?
3. How can we use regional and global climate models to predict seasonal precipitation and turbidity exceedance levels?
4. Where are hot spots of high potential soil erosion, what types of current land cover as well as land cover change are most responsible for high erosion potential?

Flow Extremes in the Clackamas River Watershed

Research Questions

Changes in precipitation, average seasonal temperatures and sea level rise may have an impact on seasonal flow patterns and water levels, potentially leading to an increase in flood hazard. Two primary questions were considered: *(1) Can we see significant changes in flow patterns over the past hundred years from the flow record for the Clackamas River? (2) Will the likelihood of flooding in the Tri-City Wastewater Treatment Plant increase with increased sea level rise and/or increases in peak discharge during a flood event?*

Research Approach

To examine long-term changes in river flow that may be attributable to climate change or development, statistical studies were performed on the more than 100-year long Clackamas River flow dataset at Estacada (station number 14210000) available from the USGS. In order to evaluate historical and modern conditions, the data was separated into two sets, with the first 40 years representing the historical time period and the last 50 years representing the modern time period. These periods were then examined separately to see if there were significant differences in the records. A Generalized Extreme Value function was used to estimate return period magnitudes, while a monthly hydrograph was produced to examine possible changes in seasonal flow patterns.

To determine the likelihood of increased flooding at the mouth of the Clackamas due to sea-level rise and altered precipitation, a Delft3d FM hydrodynamic model was developed from the Pacific Ocean to the head-of-tides of the Willamette, Columbia, and Clackamas Rivers. Based off of previous work for the City of Portland, the model was modified to include the bathymetry of the Clackamas River to the end of tidal intrusion near the I-205 Bridge. We then modeled the 1996 Willamette Valley winter flood, which flooded the Tri-City Wastewater Plant and the delta-region of the Clackamas River. In order to simulate the effect of an increase in sea level, we increased the base-height of the ocean by 0.6 and 1.5m, based on the expected range of sea-level rise predicted for the Pacific Northwest by the year 2100 by the National Research Council (2012). Additional scenarios were run with a 10% increase in runoff, following peer-reviewed literature which suggested a 0-20% increase in precipitation run-off in future climate scenarios (Najafi & Moradkhani 2015).

Findings

Changes in Flow Patterns

Overall, evaluation of Clackamas River flows suggests that annually averaged flow increased by 7% between the 1908-1948 and 1967-2017 periods. At the same time, extreme flows above 1000 m^3/s have become less common, going from a probability of .0894 in any given year historically, to a probability of .0696 in the modern period. River flow appears to have shifted to a more rain-driven system, with greater winter flows and less snow-melt driven flows, following trends also observed in the Columbia River (Naik & Jay 2005): in December, flows increased by 17%, while June flows decreased by 16%. A shift to a larger winter hydrograph but less summertime flow could be a significant concern, if combined with warmer summers and larger summertime water demand (due to development) in the CRW.

Flood Risk at the Tri-City Water Treatment Plant

Model scenarios suggest that the sewage treatment plant is vulnerable to increased flood risk from both sea-level rise and increased run-off in both the Clackamas, Willamette, and Columbia River watersheds. Model results found that with the moderate (B2) and high (A2) sea level rise projection scenarios caused an increase in the modeled flood heights during a 1996-type event by 0.16 m and .44 m respectively. When a 10% increase in runoff was included, the water levels at the mouth of the Clackamas increased by.78 m in the B2 scenario and .98 m in the A2 scenario, respectively. The A2 scenario is described by the IPCC as a world more divided, with a lot of regional economic and population growth and a focus on the economy over the environment. The B2 scenario also describes a fragmented planet without large scale global collaborations, but one that does focus on reducing emissions rather than just economic growth. Interestingly, water levels at the mouth of the Clackamas depend on the Willamette but also on the Columbia River flow, which causes water to back-up to Portland and further upstream. As a result, management decisions made on other watersheds significantly influence risk, in addition to sea-level rise. The modeled increase in flood risk would likely increase the likelihood of damage to the Tri-city sewage plant, possibly increase the time of service interruption, and potentially cause water quality problems.

Table 3: Flooding increases under sea level rise and runoff increase scenarios

Sea Level Rise Scenario	No SLR (0 m)	B2 (0.6 m)	A2 (1.5 m)
No Runoff Increase		0.16 m	0.44m
10% Runoff Increase	0.66 m	0.78 m	0.98 m

Implications for Clackamas River Watershed Resilience Project

The shift found in seasonal flow patterns is consistent with observations of increasingly dry summers and less snow in the watershed, which could increase fire risk in the watershed. With more winter flows, there could also be an increase in sediment transport during the winter months. The lower flows in summer could also cause issues for water management, influencing water temperatures and causing trade-offs between environmental and regulatory needs (e.g., the needs of salmon for higher summer flows) and consumer needs (higher summer water demands) that may occur in the future.

Next Steps

Future areas of investigation may consider:

1. Given the changes over the last 100 years in flow seasonality and extreme events, what can be projected for future changes in the Clackamas River?
2. In a future scenario, what is the smallest size flood that would flood the Tri-City wastewater plant? How likely would this flood be?
3. How do altered flow patterns affect water temperature and turbidity

Fire Risk in the Clackamas River Watershed

Research Question and Approach

It's likely that climate change and development will have an impact on fire in the Clackamas River region. To more fully understand what this may mean for water quantity in the region, researchers, we sought to understand the relationship between water and fire in the region. The primary research questions we asked were *(1) What are the main climatic drivers of fire activity in the CRW as a whole? (2) What is the impact of fire on water quantity prior to and following fire events?* The motivation for these questions came from both process-based simulations and statistical modeling efforts, which coincide in that the area on the western Cascade mountains, including the CRW, will experience a rapid to very rapid increase in fire activity by the end of the century.

Research Approach

For both question 1 and 2. , we relied on climatic and hydrologic parameters at the Estacada weather and gauge stations and also from gridded high resolution products (i.e. PRISM) during all recorded fire years during periods in the records with robust data. Conditions in the parameters during each of the fire years were aggregated and compared against parameter aggregates (or composites) during non-fire years using Superimposed Epoch Analyses—an approach commonly used in climate-fire sciences and that relies on MonteCarlo simulation to identify significant anomalies when compared to mean conditions. Analyses were conducted to test for disproportionally high or low values of the parameters during fire years (in comparison to non-fire years) during days prior to, during and following the day when fire events in the CRW were first reported. Special attention was paid to detect anomalies or departures as far in advance prior to fire events to aid managers with better preparedness.

Findings

Fire activity is driven by high drought conditions

From all eight climatic parameters analyzed, it was found that fire activity in the CRW is primarily driven by disproportionally high drought conditions (i.e. dry and warm conditions) during the summer of the fire event (i.e. dry conditions from previous years were not significant). This drying effect was observed up to ca. 2 months prior to the date (i.e. August) when most ignitions that became wildfires were first recorded in the CRW. The climatic parameter that reported the highest (i.e. most useful for manager) difference between fire years and non-fire years was the Vapor Pressure Deficit (VPD), which measures how easily moisture flows between the soil and vegetation and the atmosphere; in other words, how 'thirsty' the atmosphere is.

Peak Vapor Pressure Deficit and Fire

In contrast to non-fire years, during fire years VPD peaks in August right about 1-2 days before the start of wildfires. This peak in VPD (and fire starting date) is roughly 3 weeks later in the summer compared to the timing of the VPD peak during non-fire years. Based on this, we recommend that managers carefully track the behavior of VPD throughout the summer, especially August, when a continuously rising VPD peaks roughly around mid August.

River Discharge and Fire

In general, mean daily discharge in the CRW at the Estacada station declines during summers to significantly below mean annual levels sometime in June and only recovers in late September/ early October. It was found that mean daily discharge during fire years reaches significantly below-mean levels roughly 7 days earlier than during non-fire years. Instead, almost no difference was found between the timing of post-summer mean daily discharge recovery between fire and non-fire years; i.e. the main difference in terms of mean daily discharge during fire years (in comparison to non-fire years) are prior to and not following fires.

Implications for Clackamas River Watershed Resilience Project

All research on fire confirms that fire activity is increasing across the West and it will continue to increase. Understanding what drives fire activity at the scale of the CRW is a paramount need. In terms of the Finding 2, managers can use our lessons to prepare for seasons with higher vs. lower fire probability. For instance, if VPD does not peak in June nor July, and continues to rise in early August, there is an increased probability of ignitions to successfully spread, as fuels have been and continue to dry over the spring and summer. Instead, if VPD peaks before August and declines steadily during early-mid August, it is less likely that ignitions in the western Cascade mountains will spread, as fuels might not be prime for rapid fire spread. Finding 3 highlights and further support the use of available metrics by managers to determine summers with higher fire risks than others. It turned out that managers could also use water discharge decline timing to predict years with higher fire probability. Instead, and leaving impacts on water quality out, it seems that the recovery in discharge to “normal” levels occurs almost at the same time, regardless of fire occurrence.

Next Steps

Our initial analysis provided some information about the relationship between fire and water in the CRW, for next steps we will consider how these drivers may change with climate change, how climate change scenarios may impact the risk of fire in the Wild-Urban Interface (where communities are located), and how fire and drought impact water quality.

Appendix A – Qualitative Interview Themes

The following includes themes and quotations from interviews (n=18) conducted with natural resource managers and planners about watershed resilience in the Clackamas River Watershed. Open-ended interviews were conducted between October 2017 – January 2018. General topics covered in each interview focused on the following:

A. Threats to watershed resilience
B. Adaptation and responses to watershed resilience threats
C. Stakeholders in Clackamas watershed resilience

In this appendix we present both topical themes that emerged from the interviews (regardless of how common or uncommon they were), and where appropriate quotations that provide context and depth to the types of responses given.

A. Threats

1. Water Quality
Biggest concerns – human health and fish health
Water temperature
Habitat degradation
Contaminants
Algae
Algae combined with pre-chlorination in some intake plants
Bacteria from failed septic systems
Bacteria from human waste- camping near water, recreation on water
Bacteria from livestock, horses, manure
Chlorine in large holding ponds at nurseries- flooding during big rain events
Disinfection byproducts from chlorine- combined with organics- can be cancer causing
Fuel and oil spills
Garbage/pollution from camping and recreation and homelessness

Hazmat spills
Hydrocarbon runoff from roads
Industrial runoff
Lack of dilution of contaminants in the water from hotter, dryer summers with less winter snowpack
Organics
Other garbage dumping- including asbestos waste products from construction sites
Personal care products (not regulated for drinking water)
Pesticides- nonpoint source movement- rain water, storm water, leaching, legacy pesticides
Pharmaceuticals
Potential future of an approved gas pipeline in the CRB
Potential of future use of fire retardant-phosphorus- contributing to algae blooms
Potential threat of terrorism targeted at drinking water systems
Residential fertilizers and other chemicals
Roadside spraying
Small amounts- but cumulative impacts can be unknown
Treated wastewater releases directly to the Clackamas in Estacada, and into the tributary Tickle Creek
Various contaminants from stormwater runoff- metals, toxics
Sediment/Turbidity- hard to filter drinking water
Badly planned logging
Erosion from roads
Forest fires
Landslides
Soil erosion from nurseries and farms
Soil erosion from removal of stream vegetation
2. Water Quantity
Scarcity/Insufficient flow:

Climate- hotter, drier summers, less snowpack, amplification of drought
Competing needs and interests- drinking water, fish habitat, irrigation (residential and agriculture), recreation, industry
Curtailment on new water permits
Curtailment plans don't trigger unless there is a drought declaration by the governor- otherwise it is voluntary.
Dependent on one source. Alternative water supply scenarios –like hooking up to Portland's system- are really expensive.
Fish- not enough water to push them downstream, not enough oxygen in the water, not enough feeding rings downstream, not enough stored habitat.
Lack of dilution in waste stream (more concentration) is harder to treat. I.e. "dilution sometimes is a solution to pollution"
Lack of ground water use monitoring
Lots of impoundments and ponds, smaller dams on unnamed creeks- impact flow and groundwater base flow
Low flows impact recreation in summer months
Most water providers make most of their money in the summer months when use is highest, difficult to communicate curtailment when income is needed to cover expenses.
Population growth- water districts and agencies are mandated to provide drinking water regardless of population growth
Timing of precipitation changing seasonally, impacts water availability for irrigation
Water reuse for crops doesn't allow for recharge of groundwater
Flooding:
Balance of property owners' rights and maintaining floodplains for protection against flooding
Climate- rain on snow events leading to flooding
Future sea level rise, combined with high tides and rain events/snowmelt – risk for flooding
High impact rainfall events linked to atmospheric rivers pushed water treatment plants to the limit and caused flooding.
Historical floods in the CRB have changed the landscape – 1964, 1996, 2008, 2009, 2011.
Small degrees of difference in the amount of precipitation can lead to "hellacious big floods" versus slow flow from snow melt, which makes for uneven seasonal energy generation at the dams- producing less power, leading to less money to invest in things like fish protection

3. Development/Urbanization/Population Growth
Current infrastructure cannot handle “what is coming down the pike”. “With more and more people moving here and more and more development in our service area combined with higher impact rainfall events, there's a lot of things that are coming at us that we have to be able to handle, as a utility.”
Hilly terrain of the development in Happy Valley doesn’t allow for a lot of infiltration.
Increased impervious surfaces leads to increased “flashiness” of the system. “As you develop and you have more impervious area and you have less stormwater treatment, you're fundamentally altering the watershed's own, what's the word, sort of resilience. So, it's unquestionably part of the equation and part of the puzzle, but I think it needs to be addressed more at the level of the entities that are responsible for permitting that development.”
Increased population results in increased use of recreation in the upper watershed, overwhelming and challenging the system. CRB “loved to death”.
Increased rural growth anticipated in the future- all will be on septic systems
Much of the Urban Reserves for the Metro Urban Growth Boundary are in the CRB
Need to expand stormwater services with growing population
Poor floodplain connectivity
Population “boom” in the CRB. Lots of new construction is leading to impermeable surfaces
Potential to have climate refugees moving to the area in the future
Urbanization is a threat to fish passage. “You can’t just keep adding tens of thousands of people a year into a basin and not have it have some effect.” “My biggest concern is that development simply will overtake any ability for restoration or protection to keep fish persisting.”
Urbanized areas have visible adverse effect on water quality
Wastewater treatment plants, necessary to clean and release water in urbanized areas, can have overflows during peak flow events, or discharge of chlorine that can lead to fish kills.
Water shortage for increasing population
Widening and adding roads contributes to increased pollution runoff into waterways
4. Climate Change
Bigger storm events impacting the dam infrastructure
Bigger storms could cause bigger “first flush” into streams, with pollutants like agricultural runoff, turbidity, metals and more.
Change in frequency and intensity of events, combined with land use change

Changing summer weather patterns- hotter, drier for longer lengths of time
Climate change impacting water supply, exasperating summer droughts
Climate change impacts on ocean habitat for fish (important to fish runs in the Clackamas)
Climate change uncertainty prohibits accurate long term planning for infrastructure and adaptation
Climate refugees moving to the CRB, which will have more water than other regions
Drinking water availability is a concern
Extreme weather in the past has required complete campfire bans in recreation areas
High impact rainfall events, concerns over too much water in too short a period of time. Overwhelm wastewater treatment infrastructure.
Impacts on management activities- how to build resilience into the landscape
Increase in development and impervious surface combined with the potential of more storms impacts clean water.
Increase potential for blue-green algae blooms.
Less resilient forest is less able to fend off mountain pine beetle
Less snow pack, low flow in the summer months. Impacts recreation, temperature, concentration of waste stream flow, drinking water availability, irrigation water availability
Potential increase in frequency of atmospheric river rainfall events, combined with warming weather globally.
Sea level rise, tidal impacts to the Clackamas River and risks to wastewater infrastructure
The county does not currently have a climate action plan
Timing of precipitation impacts agricultural community and irrigation needs, need to change farming practices.
Wildfire risk associated with a changing climate
5. Other Threats to Water Resources
"We might even add one more risk there to your list, and that is the underfunding of our federal land managers dealing with forest service. Those guys have a heroic and almost impossible task in a world that still treats their budgets as being based on the production of natural resources [...] That's really ranks right up there in my concerns, because it affects us directly, because law enforcement, support science, management of invasive species on their part of the land, and I mean, all of their resources will [...] they do a nice job, but shoot, if they lose more of the staff is going to be tough."
Aging infrastructure combined with stressed systems

Crustal earthquakes- damage to infrastructure
Forest fire threat limiting repair and maintenance activities in the summer months (repairing Timothy Lake dam was an example- dam was open for repair, but fire risk required a stop work scenario, which could be catastrophic when rains arrived in the fall)
Forest fires – not just increase in sedimentation but also resulting in the loss of filtration
Hazmat spills harming infrastructure
Terrorism targeted at drinking water infrastructure
6. "Keeps me up at night" Threats
"And what does keep me up at night too, when it comes to messaging is not getting to the vulnerable populations. People who do not speak English, kids that are in school, homeless. Those that may have mobility issues or hearing and seeing issues. That keeps me up at night."
"I can't say there's anything that's that gripping, but I think what is concerning and kind of hard to get your arms around, something that I know is a problem and my colleagues know is a problem and we're still trying to figure out how best to manage it through our agency, and that would be just plain old development and the various people and entities that are involved that aren't necessarily coordinating on long-term planning and longer term hydrologic impacts of development."
"I think my biggest concern, again, is just the idea that, will we be ratcheted off how much water we can take."
"If I did have a worry that kept me up at night, it would be, should a gas-line be approved that would cross our basin."
"I'm on call on the weekends waiting for ... all the deputies have my number. I mean, obviously, I'm concerned in the sense that something big will break out. There was, anecdotally, I think it was back in 2008, there was some near-rioting going on [...] I think it's really some big social disruption, would be the issue."
"My keep me up at night scenario is effluent releases from wastewater treatment plants that kill fish directly. City of Sandy goes into Deep Creek that flows into the Clackamas, and there are incidents where they have killed fish as a result of a chlorine effluent release. So we've built these infrastructure in and around our streams that are meant to control the development around the stream, but they create such a risk for the tributary stream that, in particular, through this process with Tickle Creek and seeing how DEQ is regulating it, it concerns me for where those things exist elsewhere and are doing the same thing."
"Potentially, in the future, if we were to have a high tide event combined with a sea level rise just because we have the oceans rising due to melting ice caps, combined with high rainfall or snow melt events coming down the mountainsides as just part of the regular river system, there has to be some place for that water to go [...] you can have a pretty serious inundation event that will last a long period of time until eventually the tide goes out [...] Those events can be pretty serious. Two of our largest, most important facilities are right on the riverfront of these tidally forced areas. It is a potentially hazardous situation for us in the future should those stars align. You do need to get all three of those things coming into phase. Potentially, in

the future, if that is going to happen, that's a big deal. That only has to happen once for us to feel the severe impact.”
“The other is the crustal quake. Of course, Cascadia gives me ... But we have a lot of crustal quakes too that could really disrupt water service”
“There's a couple things. One of them is the '64 scenario. The 1964 scenario [...] The 1964 is actually the '96 flood on steroids. I mean, that scenario just makes my stomach hurt. It was just the Willamette, it was all the way down to Salem, I think. It was just horrific. That's one of the most dramatic. And then '96 of course, after that. But '96 wasn't even that bad. That one keeps me up at night because I know it's happened here, I know it will happen again.”
“Well, I wouldn't say that there is any credible, immediate threat that keeps me up at night. Any time you have a series of dams along a waterway, there are risks associated with those structures. Thinking of some worst-case scenario of a dam failure, that's something that is highly unlikely, and there are measures in place to protect people. PGE has sirens and a whole system of safeguards in place, so it doesn't really keep me up at night, but that would be something... that would be terrible for both people and the affected environment. And then the other something that could be catastrophic but is probably an outlier has to do with some kind of catastrophic wildfire that leads to landslides or just, denudes the landscape of vegetation leading to really severe impacts to the soils and water.”
“Well, you know, to me it's pesticides... We rely on the streamside buffers and filters, but we don't have any way of protecting groundwater really. We don't have a way of managing people's water usage. The worst that could happen is I see an irrigation stream running off their site and I could sample it, and if it tests positive for pesticides we could say you need to do these things. So, it's hard to enforce from my point of view, but I really believe that's the future of water quality.”

B. Adaptation/response to threats

1. Adaptation Opportunities
“And Rock Creek confluences an area, that we had a recent project in 2015, where then, when the drought occurred, it was contributing 10 degrees cooler water, than the main stem head. So, all of these tributaries coming into our main stem, even in the most lowest regions of the Clackamas, have good opportunity to provide some food, and water.”
“As a 21st century millennial public administrator, I know you can't do everything yourself. It's better to break down the silos and apply knowledge or research or work that's been accomplished elsewhere. We have what I would call sibling agencies also here in the Portland Metro Area. Within the City of Portland, of course, our Bureau of Departmental Services, Washington County's Clean Water Services, City of Gresham and then looking up and down the Willamette Valley, City of Salem, Corvallis, Eugene. Springfield has a large consortium and then looking further to our neighbors to the north, Clark County, Washington. Then looking up to our friends in the Sound area, the Water Alliance, which is in and around the Olympia, Lacey area, City of Tacoma, Pierce County, King County, which is huge and they do a lot of heavy lifting because they have a very large population to serve. They have also a very challenging service area. In and around Seattle, it's very hilly so they do a lot of great work within the City of

Seattle. Looking at the Clean Water Agencies, there's an Oregon Association of Clean Water Agencies and then there's the Pacific Northwest Clean Water Association, which is called the PNCWA and the other one, we call it OCWA. Those different groups are the trade organizations that represent the interests of storm water, wastewater, drinking water interests in the region. Because those different groups all have similar missions or are held at the same regulatory standards, we're all facing the same types of challenges, just maybe hinged slightly differently depending on where you are [...] Learning from those different agencies, the work that they've applied, whether it's something in modeling efforts or they've been trying a new storm water management design criteria or they've used some new efforts to try and redesign their infrastructure, their pipes, whatever, learning from those folks and having those relationships is the most important [...]"
"ASR, Aquifer Storage and Recovery. And so, the theory of that is, in the winter when there's so much water in the river versus in the summer when there's limited amounts, is to take the water that's plentiful and treat some extra and put it into our system and then drop it into some aquifers. So in essence, we mound up aquifer. And then in the summer time when there's less water in the river, we take that much less out of the river at the time, and just draw from that mounded up aquifer level.And so, it takes away the need to take as much from the river and puts it back on, just getting it from within the system [...] we have one well, and we've ... so for instance, we've stored 55 million gallons, is the most we've done. But, the idea would be ... and we can pull one MGD out of that per day. So again, if our peak is 12.8, then almost 10% could be met by that. So that's 10% less that we would be taking out of the river on any given day. And the idea is, as part of our planning, master plan, is that we would have more of those, you know, maybe even like 5 or so." This water could also be used to help stream flow for habitat in the low-flow summer months.
"I do think that an opportunity exists for research, and then promoting the Clackamas as a model, for how we're able to accommodate development and growth, while protecting a source of drinking water, and the natural resources. Being right here in the metro area, a lot of development pushing outward. The Urban Rural Reserve Controls have buffers of 100 foot. In certain areas. And maybe beyond that, and others. So, the longterm effects and benefits of such programs."
"I don't mean to say this to diminish people's skills or understanding, but how do you educate people better to then know how to deal with the issues? We have a great opportunity, I think, in the Portland Metro Area to have a large volunteer base and probably a lot of people that are interested in seeing the river protected. They just don't know what to do."
"I think if a program in DEQ were developed, as opposed to single issue where they have to get a crew together and go out, rather have a program around it to ... Who is monitoring these urban watersheds, and what's happening with peak flows in the winter, low flows in the summer? I just don't think anything's being done to see what's happening."
"I think what I put here is we need to listen to what the river's telling us and start to make changes before [...] that we're not recognizing that something like 2015 is going to be a more regular occurrence. We need to think long-term. We're just not doing it. As much as I think people were scared when climate change and everything became an issue, I'm afraid that's died down a little bit. People just aren't thinking far enough ahead."
"Ideally if we had a better understanding in regards to climate change, that might adapt some of the ways that we look at our water system planning in the future of all right well we're going to

have to have treatment plants that have more technology to deal with this array of stuff coming into us on a more frequent basis. Or we're going to have to upsize treatment plants so that we are going to have longer hotter summers, and unless we can really get people and tell them they can't water, or get reductions and water use down, we are just going to have to have bigger plants to accommodate that.”
“It's because of voters, it was seen as a mandate to the state, and to our legislators. In 2010, when the voters voted ahead of the sunset support to OWEB, and for lottery funds to be dedicated to protection of our natural resources, that there is political will.”
“Just real quick to touch on PGE and the hydro facility, they're proving that they can have an operation there with minimal impacts to fish currently. That doesn't talk about the legacy effects from developing the hydro projects in the first place, but their current operations, they're demonstrating that they can get fish to survive. It's something, if in this process we can demonstrate that because it needs to be demonstrated to other basins in the Willamette that it can be done as well.”
“Simply sitting down and meeting face-to-face. We do so much communication now via email and phone and the convenience of those that I find that sitting down and talking through the issues is incredibly beneficial. We try to do that often times with the federal agencies. We've sat down with NOAA often times, and you get to talk about issues and how we can collectively work together on them. It just doesn't seem to happen on a frequent enough scale.”
“That's a good example of restoration of flows, what they can do. PGE used to have a minimum flow of, I think, 20 CFS for years. Now their minimum flow during fish migration periods is 120 CFS, so there's six times as much habitat available for fish now. Spring Chinook are using it, which is something we didn't see happening, but now it's again the ability of spring Chinook to expand their range and use habitat that they've historically used that was only limited by the fact that they didn't have the water.”
“The upper basin that is relatively protected by the forest that surrounds it and what I feel now is something that is protective enough for that area. The forest seems to be an area that we can rely on in the future. When we talk about climate change, I think the Clackamas, in particular, not being a glacial-driven stream, is one that won't suffer the highs and lows of climate impacts as other basins will.”
“We're finding recently, with PGE's improvements, is that, say, spring Chinook are now using more of the basin because they're not delayed at project. They used to be delayed, so say a month delay. Then they would only get to their spawning area, which may not be fully utilizing the basin. Now they are, so that's very encouraging.”
A generational shift in the farming communities comes with opportunities to try new communication strategies and outreach about best practices.
A strong law enforcement presence on the river has a nexus with water quality improvements.
Clackamas Partnership: “It's a partnership that we have between all the watershed councils, like Johnson Creek Watershed Council, the North Clackamas Urban Watershed Council, Greater Oregon City Watershed Council, and the Clackamas because the Clackamas population for fish actually includes those tributaries. What we're doing is we're coming together to do that identification of limiting factors and threats and then develop a proposal to OWEB for pretty

significant funding, up to $2 million to implement restoration projects. This is one group that I think is a perfect example of what needs to be brought together to do these things. There's a good, similar example in the Sandy, with the Sandy Basin Partners, that all of these groups have come together to work together to deal with the issues. I think we're getting there in the Clackamas with this group. What we need is that funding to make it happen. The CRBC has a large role in that group because they're the most funded, the most capable."
Conservation programs- like indoor plumbing codes (low-flow toilets, faucets, etc.)
County hazard assessments that are updated every two years are an opportunity to bring many stakeholders together- water providers, fire, law, public health, social services, etc.
County Parks and Forest funding strategies: "And kind of the interesting thing to that, it's the timber receipts that come back to counties, come off of the timber sales, and since we're using some stewardship, those timber receipts don't come back to the County. So what we've done instead was, moved a lot of the retained receipts and the projects that would benefit Clackamas County as kind of an offset. So like culvert root placement, that both has a public safety and fish passage benefit, would be funded. A number of Cheryl's projects [CRBC], and some of the county projects get retained receipts. We were on a program called Dump Stoppers, which it cleans up illegal dump sites on forest lands, and so we've been able to get some funding through retained receipts to help run our Dump Stoppers program."
Create forums for sharing information and strategies- for example workshops with other basin coordinators, technical assistance workshops, etc.
Create resilient forests to fend off epidemics, which can lead to more dead trees and fuel for forest fires.
CREP/NCRS program pays landowners to plant riparian buffers.
CSWCD can be a grant maker instead of a grant taker because the voters voted in a measure to fund annually 2.2 million.
Development of a county-wide surface water district is in the beginning stages. This allows for integration and efficiency in regulation across agencies – roads, culverts, flood plains, etc. King County in WA and Washington County in Oregon have similar set ups.
Different funding sources can allow for different opportunities. Funding from ratepayers can open up avenues for capital projects that in a different setting would need approval from a politically elected or appointed board. There is more flexibility this way. Matching grants is another opportunity (DEQ). Lottery funds can be used for education and restoration.
Explore adaptive management in the face of climate change uncertainty.
Federal, state and local partnerships to manage forests. Also opportunities to work with tribal partners- water quality and quantity issues effect everyone.
Find a common denominator through naming the issue that stakeholders with varied values can get behind- like "drinking water".

Find a way to incorporate everyone's data to make it accessible in one place. DEQ is working on this for water quality.
Fire preventions activities- like prohibiting target shooting.
Focus resources on the county septic program- help people upgrade failing systems.
Help landowners deal with invasive species, plus advocate for more shade planting near the tributaries and rivers. Win-win. "shade our streams" program
Maintain regulations around flood plains and riparian buffers.
Micro efforts can contribute to the whole: "There are things that we look at as far ... I mean a lot of them I would characterize as micro, where we look at, oh, are bags still being used along catch basins? They're micro, but I still think they're pretty important as well. Just those kinds of things of erosion control, best practices on a site."
Monitoring and management is the future of water quality.
New technologies, like DNA testing, have helped with water quality monitoring.
Opportunities to change minds and create credibility and trust at a neighbor level.
Opportunities to reduce fuels for forest fires through thinning projects.
PGE changed operations to reduce travel time of water at the Farady dam in the summer months to help control warming of water.
PGE funded habitat projects and water quality and quantity improvement projects (millions of dollars' worth)- partnering with the CRBC and others.
Promote septic program as a public health issue- messaging to public and to politicians.
Regarding river flow and dams: "It's what the natural resources in the river, the fish and the water critters expect to see. So, we're not trying to make it better than natural, we're saying if they grew up facing big spring runoffs then they should face them now. So that's kind of the long-term goal on that project."
Reintroduction of species from other basins (i.e. reintroduction of bull trout in the upper Clackamas from the Metolious River.
Retrofitting pumps in irrigation wells at nurseries to use less energy and to meter water better.
Reusing "purple pipe" recycled wastewater for irrigation.
Robust fish monitoring programs at the dam- keeping track of juvenile and adult fish, sorting wild from hatchery fish and only allowing wild fish above the dam to create and preserve a wild fish sanctuary.
Salmon education in schools- CRBC program
Stash the Trash bag program on the river for recreation garbage curtailment

System Development Charges- give cities the capacity to require certain infrastructure investments from developers on new projects, including providing open space.
The Clackamas Partners (different than the Clackamas Stewardship Partners) is a recently formed group that includes a variety of stakeholders. "This group is looking at the Clackamas River Basin as a whole [...] but they're really looking at: what are the watershed and restoration needs in the basin? Where should we put limited resources? What are the priorities? This group is working together to come up with an updated action plan. They formed one a while back, but they're revising it, renewing it, taking a fresh look at conditions that may have changed since they developed their last plan. Through this plan, in terms of funding for restoration work, projects that can attract a variety of funding sources are often the most likely to get implemented, and so having this action plan might help all of us strategically think about how we're going to help support the priorities in the land."
The local planners have the flexibility with code to make exceptions that can help minimize impacts of development, for example reducing required parking in an environmentally sensitive area.
The regional stormwater managers Clean Rivers Coalition is a great way to send one message in one voice to the entire Willamette- a great model for outreach and communication with stakeholders.
There are opportunities for better storage and disposal of agricultural chemicals.
There has been a lot of coordination in the basin about water quality and fish habitat, there is the opportunity to tackle the issue of water quantity too.
There is going to be more opportunities for collaboration in decision-making
There is the need for a more strategic and integrated plan for water curtailment in response to drought.
There is the opportunity for the county to develop a climate action plan across departments- linking to state, and international climate goals.
Volunteer projects to raise awareness and community buy-in.
With regards to climate change: "We coordinate well, both internally and with external partners, but it seems like if you think of the threats to water, there's a lot more coordination that could be done in terms of the science and its application, how we implement that. I mean we are science-based organization, but I still think that there's probably more work that could address the uncertainties and then also the realities of land management."
Work with ag chemical sales reps to help educate about appropriate amounts of application (more is not always best).
2. Barriers to Adaptation
"[...] they really need to work on getting those quality, QAPs, the quality assurance plans out, and, because, [...] we couldn't use any of the, so DEQ for us just started doing this [...] is gathering data in their database and running a status and trend analysis for our management area and then reporting the results to us. What we're finding is, you know, there may be 500, 150 data

sets, but they're only able to use five because the other 100 either didn't meet the type of quality or it didn't get downloaded right, or whatever reason they couldn't use it."
"2015 is the example of what happens when you get ultra low flow, high water temperatures, and fish died as a result. We had a big die-off of spring Chinook during that year, and it provided us a really good picture of what it might look like in 20, 30 years, on a more regular occurrence."
"I would say that right now, we have adequate resources, but our budgets have been remaining pretty static in recent years, if not declining. With that happening, it makes it ever more challenging to maintain the staffing levels that we would like, to provide the goods and services and protections that we offer."
"If you don't understand the problem, you're not going to want to fix it. And I think rural landowners and ag landowners don't all, they intuitively have a better understanding of water quality than maybe an urban person does because they're out there working in it every day, but at the same time they don't really know the status of their water quality. They don't know that they're living on an impaired stream. They don't understand that."
"One of our mandates is that we provide water to the areas that are within our boundaries and the other one is, again, we have that relationship with city of Happy Valley as part of the water authority. So, as they move somewhere, we too are supposed to move and serve that area. So, we kind of just are sometimes in the reaction mode [...] we aren't the ones deciding how it develops. We don't have say in what industry goes where and how much water they can or can't use."
"Something that I know is a problem and my colleagues know is a problem and we're still trying to figure out how best to manage it through our agency, and that would be just plain old development and the various people and entities that are involved that aren't necessarily coordinating on long-term planning and longer term hydrologic impacts of development."
"There's a lot of layers and a lot of players and a lot of values associated with it. Not everybody values water for the same reason."
"This is where I've questioned DEQ and how they're regulating the large developments that are occurring. Do we size things like treatment ponds or whatever for impervious surfaces? Are they big enough? I rarely get an answer that says, yes, they are. We know they are. It's more that they use some modeling to determine sizing, and I typically think that most of those are simply inadequate, especially when we consider the impacts of impervious surface in peak flow events that happen in those watersheds. They simply can't control the water [...] There's a lot of instances where you go out and do your thing and create a storm water detention pond that's going to clean the water. Do we know if it actually functions effectively to protect fish? "
"Time is stretched too thin, yeah. Everybody is just spread too thin, but I think the opportunity and the benefit it would create would overwhelm that. We just don't do it."
"We can do everything we want to, to protect and restore fish in the upper basin. They have a corridor, and also they do rear in the lower basin as part of their life history. So you can't just write it off and let things deteriorate, as I think we are. A couple of examples of that are, again, the wastewater treatment plants. We happen to be there. We happen to monitor, so our guys are walking the stream, and they'll smell chlorine. It's really that bad. We've only had two specific incidents where fish died as a result of it, but there was one where 60 adult coho died, another where nearly 100 juvenile coho and steelheads died, directly as a result of effluent release. So

there's that, and it's a tributary to the Clackamas, so Deep Creek. Then you've got Rockcreek, which is downstream and probably the highest rate of development anywhere.”
“We need to listen to what the river's telling us and start to make changes before [...] we're not recognizing that something like 2015 is going to be a more regular occurrence. We need to think long-term. We're just not doing it. As much as I think people were scared when climate change and everything became an issue, I'm afraid that's died down a little bit. People just aren't thinking far enough ahead.”
“We're kind of an affluent area and so they tend to use quite a bit of water for water, watering their lawns. So, to give you a feel, our winter demand is more like 3.5 million gallons per day.... the difference between 3.5 and 12.8 [summer use].”
A lot more coordination needs to be done with partners to address the uncertainties that will come with climate change.
A need to be more strategic in drought contingency planning.
Able to enforce zoning, but not much beyond that
Abundant recreation in close proximity to water is problematic.
Agriculture regulation is complicated because of the large variety of types of agriculture in the CRB.
As Happy Valley takes over providing services for Damascus, what future responsibility will fall on the city regarding updating infrastructure?
Cost is a major barrier to implementing strategies.
CRBC is supported by the state general fund. Decisions are made at the legislature level, not the level of those doing the work on the ground. This makes it perpetually vulnerable.
Current infrastructure will not be adequate to deal with the increased frequency and intensity of weather events in the future due to climate change.
Curtailment plans are not cohesive or consistent in the basin, and most them don’t trigger unless there is a drought declaration by the governor. Most curtailment is voluntary.
Decisions about whether to spend restoration money in urban areas, or use the same amount of money in rural areas to “preserve a lot more fish”. How do we start tackling an issue where it can be most effective?
DEQ should be the keeper of data that can be shared between agencies, but they have not had a sustainable data management system until now (to be newly implemented soon). Right now sharing is ad hoc.
Difficult to control dumping- homeless encampments, human waste impacts on the river.
Difficult to improve old infrastructure when people do not want their water rates increased.

ESA recovery plan is not regulatory and not mandatory, it only happens if there is political will to do it. Plus, existing regulations are being peeled back.
Fisheries management is lacking in getting their message out to the public.
Focus on complaints and code violations, versus paying attention to where development is proceeding. Plus, resourced drop off in these areas because residents aren't paying to use sewer pipes- yet development is still happening.
Frequent coming and going of the farming population makes messaging around regulations difficult to communicate.
Funding to DEQ, passed down from the EPA has gone down every year. This a congressional decision, so not a local control. This means they are unable to provide grants to support other organizations like CRBC.
Happy Valley has a "really extremely low permanent tax rate", so in order fund operations the city has to go after a levy and get approval from the voters.
Higher temperatures and lower flows requiring more treatment in wastewater.
If permitting and regulations would allow for more flexibility people could share water rights in certain ways.
Increases in construction and impermeable surfaces in recent years, and projected for future years, are taxing utility infrastructure.
It is a significant undertaking to try to change the regulatory process.
It's difficult and controversial to try to balance property rights and environmental protections.
Lack of adequate law enforcement – not enough people on the force.
Lack of coordination of information between departments and agencies.
Lack of education or a public knowledge base about water in the CRB is a challenge and threat to the resource.
Lack of use of online resources for rural agricultural population- generational difference.
Legacy farming conditions are difficult and expensive to correct: channelized streams, compaction, invasive plants, etc.
Many farmers have off-farm jobs and don't have a lot of spare time to connect with education or resource opportunities.
Old infrastructure in treatment plants cannot deal with the increase in use/need.
Opportunities to do outreach to landowners depends on available funding, which is uncertain in the future.

Outreach to vulnerable populations is a big challenge (floods, landslides, fires, human health issues)- included non-English speakers, children in school, the homeless, those with mobility/vision or hearing issues.
People are shy about their data- "they don't want to be, well I shared this with you and now the government's here and they're telling us our streams are dirty and we can't do all these things and it's all my fault."
People are shy about their data, not sure if its good enough to share.
Pesticide sales reps may push more chemicals than are necessary in order to meet their sales bottom lines.
Political pendulum swings can be a challenge because the elected board governs the department.
Political shifts can shift management directives, which impacts water providers, particularly in cities where water is just one of many responsibilities of the elected officials. There is a constant need to educate the elected officials.
Regarding water rights, there is more demand than water.
Resistance to change by landowners.
Resources are not available to monitor water quality- there are not enough monitoring locations. long term data sets are lacking, and modeling is lacking.
Social media-driven events have set back efforts to change negative-impacts and behavior for recreation on the river. Now there are very large events, organized quickly that bring thousands of people in one day (Floatapalooza, The Goth Float, etc.) – it puts a strain on the system. Plus if someone is using the river just once, they don't care about the river in the same way as regular visitors. "We started seeing, from a social or cultural phenomenon, people of entitlement, didn't care about your rules, didn't care about the river, didn't care about anything but just for the next three or four hours, they were just going to do what they wanted to do."
Some agencies spend time reviewing and commenting on land use issues, but run into frustrations when it does not make a difference. Many of the DEQ regulations are not sufficient for water quality. "It's not enough. When you look down the road and, in particular, consider climate change, they're not. One question that I often times have for the regulators that we work with is how is this going to make a difference. What difference will our comment or our effort to review something make in the overall implementation of the project? So it's got to that point where, because we're spread so thin, unless we know we're going to make a difference, we don't get into the arena anymore."
Staffing issues result in the inability to be proactive.
The biggest risk to the river is the overuse by people for recreation with very little control over access.

The combination of drought and future climate change have not been considered in planning yet. The needs will vary in different parts of the basin too (South County has been particularly impacted in the past).
The future of EPA funds significantly impacts the Pacific Coho Salmon Recovery Fund that is distributed through OWEB.
There are not systems in place to deal with severe events, rather they are handles in more of an ad-hoc manor.
There has been a focus on technical solutions, but there is a need for more planning and collaboration on sharing resources.
There is a conflict in priority between the county tourism department and the park department. The Park department is not interested in attracting any more people to the river since it is already strained system.
There is a tendency that water decision-makers will "go at it themselves", instead of collaborating.
There is an increase in development of areas that are not serviced by sewers, therefore they are on septic, and these areas are not well-mapped, lack regulatory mechanisms, and sufficient funding to fix it.
There is difficulty tackling problems that are expensive and long-term.
There is not a good understanding of how climate will impact frequency and intensity of storms and how this will affect past and current riparian and habitat restoration efforts.
There is not current thinking about how to incorporate forest fire risk into watershed planning
Time is another major barrier
Traditional farming: conservative and highly focused on "safe" decisions. Conservation best practices lag behind cutting edge research.
Uncertainty about the impacts of climate change.
Understaffed- unable to be proactive
Water boards represent the people and may take exception to restrictions of water use.
Water infrastructure function and improvements are funded through ratepayers, so there is not incentive to curtail water use in the summer.
Water providers do not have their water rights determined because there is ongoing litigation from Water Watch regarding their impacts on fish habitat.
Water quality monitoring that is being done, is housed in different places and difficult to share.
Water quality reports do not get distributed as widely as they should. You have to know where to go look on a website to find it now.

Water quality sampling may decrease from agencies and nonprofits who rely on DEQ 319 grants, as that money is not longer available.
When dry years are followed by wet years the sense of urgency for drought planning declines. "Out of sight, out of mind [...] We'll be there again one day".

3. Is the Basin the Appropriate Scale to Approach Adaptation Strategies?
"Six-field watershed scale" like the lower portion of Deep Creek- it's an appropriate scale to measure and to be able to see change in restoration activities.
CRB is the right scale to address these threats (main response)
Department of Fish and Wildlife (federal) and Water Resources Department (state)
For fish, we also have to consider the Willamette and Columbia, including the Portland Harbor in the Willamette.
Individual connection is a better scale, "the best interactions happen between neighbors to establish credibility and trust". This is how to change people's minds. It is difficult to "scale up" this level of engagement.
It's going to take all levels- national leadership, state processes, the county "all politics is local", neighborhood scales
Watershed level is the right scale because you need to look at the "big perspective"- from the headwaters, transport and deposition to the ocean.

C. Stakeholders

1. Who Is Currently Engaged
"The biggest one that is the champion is the Clackamas River water providers"
"The Watershed Council is huge. I mean, the Watershed Council, I would say, is the driving force of positive change and protection in the Clackamas Basin there."
"The Watershed Council is a convener, [...] the Watershed Council is the central entity that brings us together."
"I would mention the Soil and Water Conservation District is also another really, really important source of positive work and positive change in the river basin because of their technical expertise, particularly around conservation and restoration and land management, and because of their relationship with landowners that not being a regulatory agency."
Metro- "They're an enormous significance, and they are most definitely not only at the table but I think could almost be in some cases convening other people around the table of restoration."
"I think there's an intent and a willingness to have good information sharing, but we all, when I say we, I'm talking about all the stakeholders in the basin, all have our own systems that we're

keeping our data in. I think it's fair for people to look at an agency like DEQ and say, you should be the place where all entities can send their data."
"I think the folks that have lots of data, the Clackamas River water providers because of the contract work that they've funded and contracted, US Geological Survey, DEQ, the Soil and Water Conservation District has its own data. The Watershed Council does submit their data to DEQ. There's a lot of entities that have data, and we're certainly willing to share it with each other. We just don't have a really convenient way to do that, and so it tends to be kind of ad hoc [...] I think we're all aware of it, and again the Watershed Council has done a really good job of initiating those conversations about who's collecting what where and making us aware of work that's going on, but it's a big lift for any one entity to be able to pull it all together and make it sharable."
2. Who is Missing from Engagement
Agriculture, grower groups
At times Clackamas County government
Landowners
More people need to be engaged in the big picture of land use planning, development planning, roads, agricultural conversions and forestry conversions.
"More than I feel like someone's missing, I wish I had more engagement. Because they show up. But it's hard to keep it going until we can get it all done because it takes time."
More work to do to reach the general public, the "missing middle"
Planning on a watershed scale.
"That is a really excellent question, and that's always the one we want to be asking. We think we know what all the sources are, and we think we know who all the stakeholders are, but I mean, if someone's missing, how do we know they're missing?
The academic side, scientific research
Tribes- taxed in terms of resources and time, they are "vital, key managers of land and water"
Work on better coordination amongst agencies. We work past each other a lot.
3. Is there Political Will to Address these Threats?
"I think that in general as the city's grown, the elected officials have been, that's kind of been their interest is [...] having greater local control over some of these things."
"I think we do have a concern on future support federally to the EPA, and any political direction, that dictates their responses."
"If we're looking at capital projects or things that are potentially more far-reaching, you would want to get approval from the commissioners for that type of policy direction. You have to walk

that line very carefully and use the political climate at the time as a bellwether to determine whether or not you can embark on these projects.”
“In the U.S., legal cases and precedents that push us not to unduly limit landowner and property owner rights. Again, it kind of comes back to this balancing act.”
“It's because of voters, it was seen as a mandate to the state, and to our legislators, In 2010, when the voters voted ahead of the sunset support to OWEB, and for lottery funds to be dedicated to protection of our natural resources, that there is political will.”
“My perception as a state-level environmental regulator is I think there is. I think it's a question of resources more than will. I do think that the county recognizes that they have water and land management responsibilities, obviously, and that development certainly has an impact on water and land management.”
“No, nope. I don't know how serious people are about ... Since fish protection, fish restoration, our ESA recovery plan is not mandatory. It's not regulatory. There's no reason for anybody to do anything really. Unless there's political will and somebody that can back either the ... regulation seems to be peeling back. Not that I say we need more regulation. We don't. We need to regulate what we have to regulate with the tools that we have. It frustrates me to no end that we seem to be peeling back to make it easier for people to do some of these things. So, is there the political will to stand up and say no more? We've got to do something.”
“Planning and development is really our big, big major tool. As a city that grew up from being somewhat anti-development...”
“Political will is political will. It comes and goes as people are elected into office.
“There's always the stress of where funding is, and available funding. So, there can be shifts in political will, based on creation of jobs, presence of corporations. Things like that.”
“We actually own, the county owns about 3,400 acres of forest land that we manage for timber production, that the revenue from the timber operation is one of my revenue streams for the parks, but it's also kind of our own laboratory of being able to have a voice and speak about forest policy and forest issues, because we're not just talking about it, we're living it and doing it. So we get a lot, I do a lot of work with the county commissioners on forest policy, state and federal issues affecting forest lands and forest health, and fire, and all that.”
“Yeah, if we're going to have to pay for Parks we're going to have to do a levy, which is how we do our own local police force. That's the thing that kind of hamstrings us on a lot of this stuff is that we have a low permanent tax rate and it would require a lot of political will among the citizens to raise their own tax rate permanently. And particularly to kind of entrust that the government would be the stewards of those increased revenues.”
A lot hinges on public opinion, and the county is diverse with a large urban population and also many people who live in rural areas.
Basin coordinators are funded by the state general fund. All of these positions need legislative approval, so are vulnerable when attempting to make the budget balance.

Clackamas County government has limited jurisdiction over long-range planning for water, and therefore a "pretty minimal surface water management role".
Competing science and politics regarding endangered fish listing in the CRB
Currently there is federal litigation going on between the National Marine Fishery Service and FEMA, which claims FEMA's flood plain regulations are violating the Endangered Species Act. The outcome of this lawsuit may require cities and counties to enforce larger riparian buffers and floodplains.
Federal budgets are static or declining- difficult to maintain staffing levels, provides good and services
Funding provided to DEQ has gone down consistently every year. It is dependent on congressional decisions.
On the county level, some argue that cities should be paying for more source-water protection strategies.
Planning and zoning has been in Oregon for 40 years, so most people understand that there are environmental regulations and there is not push back.
Technical side versus the opinions of individual boards or commissioners- they don't always match up
The County Commissioners can have a pendulum swing- in the past there were Tea Party Republicans, now is it largely progressive environmentalists.
The county needs a county-wide surface water district to integrate planning and management around water in a comprehensive way. This is a very real possibility in the near future.
The guiding direction for the USFS will not change without a forest plan revision, which is overdue. The earliest the revision may happen is 2020.
There are federal mandates on how water systems work, but changes at the federal level are slow.
There is an opportunity for the county to have a climate action plan and engage the legislature on statewide goals that align with the Paris Climate Accord.
There is not political will to expand the size of riparian buffers- perception that it will cause hardship for farmers by removing productive farmland.
There is political will at ODA from leadership to promote ag water quality. Currently there is not an "Ag Practices Act", but there is recognition that if things are going the wrong way then someone will say this is necessary in order to measure levels of compliance to standards and BMPs.
Utilities have city councils or elected boards, and political dynamics definitely impact decision directions. "You are constantly in this learning and teaching your elected officials what you do and how you do it, and why we need to increase rates, and how we plan our water system master plans planning into the future, and how we kind of outline the improvements we're

going to make over time, and that comes back to what do you charge for system development charges as communities are growing. It's like how does that new growth pay into the system? And it's not rocket science, but it is complicated, and as you get new people every year, you just have to continue not only to remind those that are even somewhat aware, but we educate them.”
Wastewater outfalls are not allowed on the Clackamas (exception of Estacada into the Clackamas and Sandy into Tickle Creek). As long as politicians maintain this rule, the CRB might avoid major issues with pharmaceuticals in the water.
Water board represents the people- may be resistant to restriction of water use
Yes, cities and water agencies as a group, but sometimes on an individual basis everyone still wants “their water and their right”.
4. Stakeholder Messaging and Outreach
“And unfortunately, that has somewhat to do with the way our rates are ... you know, how our water rates work in that we don't do a good job communicating to people what rates pay for, and probably we need to do a better job of making our baseline flat rate cover just operation maintenance year-round, and then ... Most people have tiered rates, so in the summer the more you use, the more you pay.”
“Once we adopted our drinking water protection plan, it became clear very quickly that there's a huge outreach component in the watershed also, so we kind of have two audiences. One are our customers, because it's their water dollars that are funding our programs upriver. And then our other audience is the people who are actually in the watershed, in that their land-use actions can impact our drinking water source.”
“There's no teeth or any regulatory requirement. But we have been engaged in our watershed since the late '90s, and I think that all of our water providers understand that and recognize that because we are one of the biggest users of the basin that we have to show that we are good stewards and that we are not taking for granted where our water resources come from. And they also recognize that the more we can do to be engaged in the watershed and help people understand, and help maintain a high quality of water, the better ability we have to keep our treatment costs low.”
A real threat is people not knowing or understanding their role in managing water quality from agriculture activities, for example manure from horses or other farm animals.
County Emergency Management does media blitzes (and social media) regarding human health and safety, including boil water announcements, flooding, fire, snow and ice, drought.
Curtailment plans vary by water providers, but most don’t want to tell their users they are required to restrict use, they would rather it be voluntary.
DEQ reports are available on their website, but people need to know that they can go look them up.

Fire danger- at times of high fire danger, crews go out and make contact with campers and implement public use restrictions. Social media is being used more for public outreach, and recent fires with air quality impacts have raised fire danger awareness.
Forestry has a set of standards and BNPs in Oregon. Agriculture puts forward conditions, and try to work with farmers to be in compliance. The conditions vary depending on the climate and region. There are 38 regions in Oregon. This makes dealing with regulations very complicated. Farmers can receive funding and technical assistance to get into compliance.
Issues with pesticide use. There is a need to partner with companies, like pesticide sales reps, to help with education of farmers in terms of appropriate amounts to apply. Homeowners need education too. Just because you can buy it and it's legal doesn't mean you need to apply as much as you do.
It's difficult to maintain the messaging- people only care when something goes wrong. It is difficult to get people to care about messaging around preparedness for future problems, like climate change.
Managers can choose language that appeals to everyone, like "drinking water" instead of just "water".
Many people are moving to the region and the Clackamas does serve as Portland's "backyard playground", so there is constant need for public awareness and outreach. The ability to do this is funding dependent.
Messaging is still targeted at outdoor water use in summer months, promoting conservation. With climate change this is going to be even more important.
Need to educate people about minimizing amount of pesticides entering the river and streams
ODA- 24 hour pesticide concern line for the public
ODA program focused on non-point source pollution works with farmers, ranchers and the ag community as a whole. This includes maintaining streamside-vegetation.
Outreach and messaging through the Clackamas River cleanups caused the commissioners to step up and take action. Bans on unsanctioned alcohol and enforcement efforts.
People really connect with salmon and steelhead messaging (as compared to other species). But messaging is still a problem in this area, it often falls on deaf ears. There is an attempt to reach Millennials, as the next generation of anglers.
Private landowners get involved with river clean up, and voluntary place garbage receptacles on their properties adjacent to the river.
Septic system owners- the county requires a report that the system is put in by a licensed installer. There is a desire by the county to have more resources to be more pro-active, like grants to upgrade systems and time to go out and market it to landowners. There is a need to pitch it as a human-health issue.
Sharing technical information with boards and commissioners

Shifts away from just monitoring, instead form partnerships of stakeholders, and share data/transparency
The Clackamas River Basin Council does outreach to the community for a number of projects, like the Shading Our Streams program, they make participants feel proud of their achievements. The CRBC is also involved with school education programs around fish.
The Clackamas Soil and Water Conservation District are the source of information, education and resources at a local scale for landowners. They serve an important role because of their relationships with landowners. It helps they are not a regulatory agency.
The Department of State Lands has "bigger hammer". They can cite people who pull out vegetation in wetlands without a permit.
The Pesticides Stewardship Program- engaged in outreach activities and assessments
There are many new farmers, people coming and going, many don't know the rules exist. Or have had years and decades of bad practices. It is difficult to connect with farmers, they often have "off farm" jobs and not a lot of time.
There is a need for better public understanding of danger to drinking water, including waste management, dumping, etc.
Use funds to incentivize people to change- irrigation upgrade projects, but must include water gauges, for example.
Water districts have a need to constantly educate elected officials about what they do and how they do it, why rate increases may be necessary, and long term planning needs.
Water quality reports distributed to landowners

Appendix B.1 – Precipitation data and methods

1. Data

In-situ precipitation data is from the Cooperative Observer Network (COOP) dataset, a National Centers for Environmental Information product. COOP data comes from a network of over 10,000 volunteer observers spanning the United States. The Estacada 2 SE (41' elevation) and the Oregon City (17' elevation) COOP stations are located near urban centers in the lower Clackamas watershed (USGS cataloging unit: 17090011). In-situ snow water equivalent (SWE) data is from the Natural Resources Conservation Services (NRCS) Snow Telemetry (SNOTEL) network. The Peavine Ridge (3420' elevation) and Clackamas Lake (3400' elevation) SNOTEL stations are located in the upper Clackamas watershed. The SNOTEL network consists of over more than 800 automated data collection sites located in high-elevation mountain watersheds. Modern-Era Retrospective analysis for Research and Applications, Version 2 reanalysis (MERRA-2) was used for atmospheric circulation variables sea level pressure (SLP), 500-hPa geopotential height (Z500), 250-hPa wind speed (V250), and integrated vapor transport (IVT; Gelaro et al. 2017). MERRA-2 is a product of the National Aeronautics and Space Administration (NASA) available from 1980. MERRA-2 has 0.5° x 0.625°spatial resolution and hourly temporal resolution. GRIDMET data was used for surface temperature and regional precipitation figures. GRIDMET is a University of Idaho product available from 1979. GRIDMET data has 1/24° x 1/24° spatial resolution and daily temporal resolution (Abatzoglou 2013). GRIDMET data combines high temporal resolution data from the North American Land Data Assimilation System Phase 2 (NLDAS-2) with high spatial resolution data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM).

2. Methodology

2.1 Extreme precipitation event definition

This study evaluates 1-day total precipitation accumulation over the 37-year time period from 1980 (corresponding to the availability of reanalysis data) through 2016. Both COOP stations were used to calculate the 90th percentile 1-day total precipitation accumulation based on wet days (>0 mm precipitation at either station). In other words, the daily wet day precipitation total frequency distribution used to identify the 90th percentile was constructed using data aggregated from both stations. If the precipitation amount at either of the COOP stations was greater than or equal to the 90th percentile 1-day total precipitation accumulation threshold, the day was considered an extreme precipitation event.

2.2 Large-scale meteorological patterns associated with extreme precipitation days

Composites of SLP, Z500, and V250 were constructed for the extreme precipitation day time series (Figure 3). These variables describe atmospheric circulation near the surface, in the mid-troposphere, and near the top of the troposphere respectively and together provide a comprehensive diagnosis of the driving atmospheric mechanisms for extreme precipitation days. The self-organizing maps (SOMs) approach is employed to identify the range of large-scale meteorological patterns associated with extreme precipitation days within the Cw. SOMs are a class of unsupervised neural networks that take, in this case, 2-dimensional geophysical data as input and sort the input data into a set of m x n clusters or "nodes" where each day assigned to a given node has weather patterns with similar characteristics as the other days assigned to that node. The SOMs approach has been demonstrated as an effective and robust tool for studying synoptic-scale meteorological patterns (Lennard and Hegerl 2015; Swales et al. 2016). This study leverages the SOMs approached used by Loikith et al. (2017) using the weather patterns at each of the three atmospheric levels for each day identified as having extreme precipitation as input to the SOM. Based on a sensitivity analysis, a 4x3 node configuration was found to optimally capture the synoptic pattern variability while minimizing pattern repetition. The 12-node structure is intended to maximize utility by practitioners.

Node composites of various dynamical variables (IVT, surface winds, surface temperature, regional precipitation, and precipitation anomaly) were created based on SOM assignment of extreme precipitation days to the 12 nodes. The Rutz Atmospheric River (AR) Catalog, based on MERRA-2 input data was used to identify atmospheric rivers (Rutz et al. 2014) for days assigned to each node. This study maintains the Rutz et al. (2014) definition of ARs: narrow corridors of water vapor transport $\geq$ 2000 km in length with integrated vapor transport (IVT) $\geq$ 250 kg m^{-1} s^{-1}. The latitude and longitude bounds used for the Rutz AR indicator were [45 46] and [-124 -122] respectively.

2.3 SWE change (Preliminary research)

This study evaluates 1-day changes in SWE over the 36-year time period from 1981 (corresponding to the installation of SNOTEL stations in the Clackamas watershed) through 2016. At both stations, the SWE time series was sorted into three classes: days of increased SWE, days of decreased SWE and days with no change in SWE. SOMs analysis as described above was performed on increased SWE days and on decreased SWE days at Peavine Ridge and separately at Clackamas Lake.

Appendix B.2 – Extreme precipitation self-organizing maps

While the composites in Figure 2 are physically interpretable and provide plausible mechanisms for extreme precipitation over the Cw, it is likely that there is considerable intra-composite variability. To identify the range of weather patterns associated with extreme precipitation over the Cw, Figure 3 shows the SOMs results where extreme precipitation days are sorted into 12 nodes. Each day with extreme precipitation recorded is assigned to one of the 12 nodes such that a day assigned to Node 1 would have a strong low pressure to the northwest, a deep trough to the west at Z500, and a strong jet streak oriented from southwest to northeast. The SOMs approach highlights the large range of weather patterns that can bring heavy precipitation to the Cw. For example, the right side of the SOM tends to be more associated with high pressure while the left side of the SOM is more associated with low pressure.

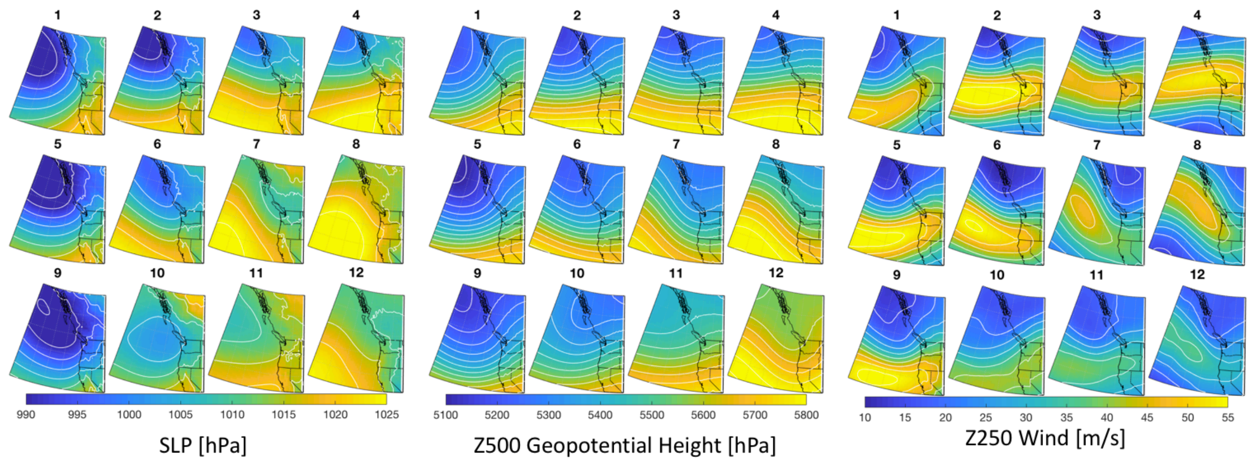


Figure 3. 12-node self-organizing maps for the 1166 greater than 90th percentile accumulation days showing (left) sea level pressure (SLP; contours at 5 hPa spacing), (center) 500 hPa geopotential height (contours at 50 m spacing), and (right) 250 hPa jet stream winds (contours at 5 m s-1 spacing).

In Figure 4, we sort the occurrence of days assigned to each of the 12 nodes by month. The circle size in Figure 4 is proportional to the number of days from the corresponding month that are assigned to each node with larger circles indicating more days. Most nodes are primarily common in the fall and winter months. Node 12 stands out as being a primarily summer pattern, which is physically consistent with expectations considering Node 12 in Figure 3 shows a much different pattern than the other cool season patterns. Node 11 also shows some tendency towards spring while Node 4 tends to be most common in fall.

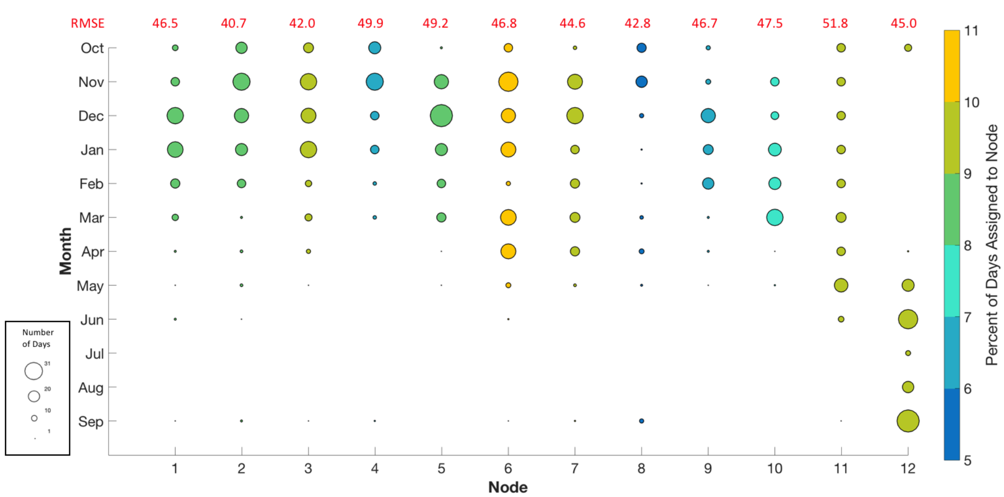


Figure 4. SOM dots plot showing node assignment along the x-axis and month along the y-axis. Dot size is proportional to the number of days in each node from each month. Dot shading indicates node frequency of occurrence with yellow nodes occurring most often and dark blue nodes occurring least.

The RMSE of each final node composite relative to all node input days is displayed in red at the top of the figure.

To get a better understanding of the mechanisms associated with extreme precipitation days, Figure 5 shows composite averages of the integrated water vapor transport (IVT) for days assigned to each node. IVT describes the total amount of water vapor that is being moved through the entire atmosphere at each data point. When IVT is over 250 kg/m/s, the threshold to be considered an AR is reached. On top of each node composite in Figure 5 is the percent of days assigned to that node that were identified as being associated with an AR according to the Rutz catalog. Node pattern association with ARs is assigned to weak, moderate, and strong, consisting of 0-40, 41-70, 71-100 percent of pattern days coinciding with a positive AR signal. There is a strong association between ARs and nodes 1, 2, 3, 4, 5, 6 and 9. There is a moderate association between ARs and nodes 10, 11 and 12. There is a weak association between ARs and nodes 7 and 8. The highest proportion of AR days occur with the strongest low pressure patterns, while the lowest occurrence is for the higher pressure patterns (see Figure 3 for corresponding patterns). This suggests that ARs are a key mechanism for bringing extreme precipitation to the Cw, however not all extreme days are associated with an AR.

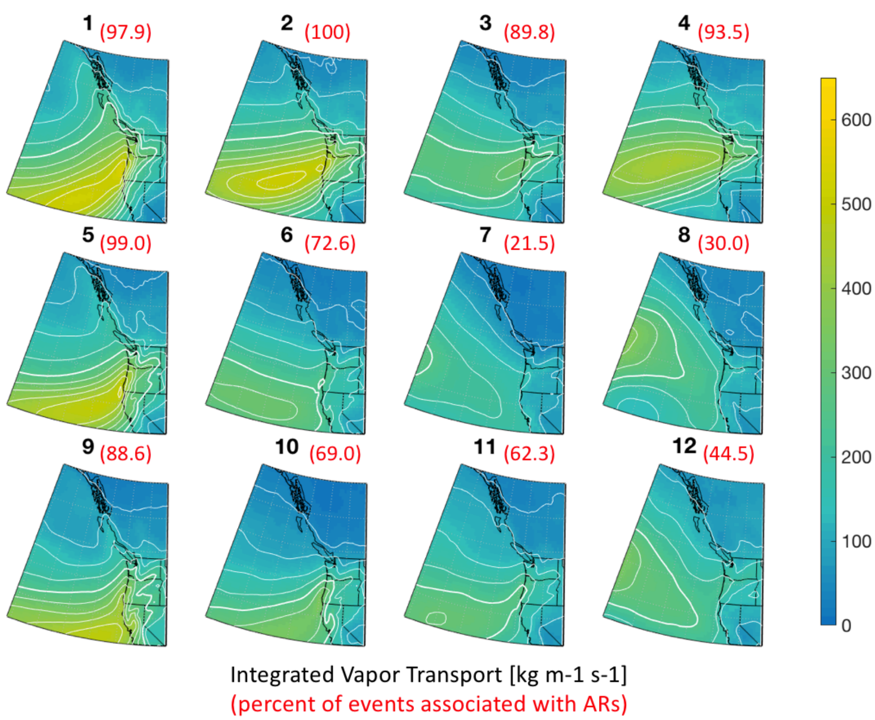


Figure 5. Node composites of integrated vapor transport (contours at 50 kg m^{-1} s^{-1} spacing). Bold contour indicates at 250 kg m^{-1} s^{-1} threshold for AR classification. Red numbers are the percent of events in each node that have a positive AR signal over the study area.

Appendix C.1 -- Turbidity, Discharge, and Precipitation Dynamics

1. Data

Three USGS gaging stations were chosen to obtain discharge data in cubic meters per second (CMS) and turbidity data in Formazin Nephelometric Unit (FNU) from the water year 2008 to 2017 (Table 1). Discharge and turbidity data collected were only analyzed for the wet season, which in this study was defined as between October 1st and May 29th. Summer months from June to September were neglected in this study because the chosen watersheds do not receive a significant amount of precipitations during the dry season. Precipitation data was also collected on an hourly basis in millimeter (mm) from the nearest Portland Hydra Rainfall Network stations during the 10-year study period. Landscape characteristic data like land cover type were collected from the 2011 National Land Cover Database (NLCD) to identify the percentage of urban, agricultural, and forest cover percentage in each sub-basin delineated from the study stations.

2. Methods

2.1 Storm Identification

Identifying storms and heavy precipitations were not straightforward because hydroclimate in the Pacific Northwest is highly influenced by seasonality, atmospheric circulation patterns, and the Cascade mountain range. Both Clackamas River and Johnson Creek are in the low-lying valleys west of the Cascades, which exhibit mild year-round temperatures, substantial rainfall during the winter, and higher accumulation of precipitation in upper altitudes. We identified major storms with corresponding elevated discharge and turbidity levels. Namely, we used a 20% threshold exceedance of the monthly average discharge. Duration of each major discharge event was limited to less than seven days. Storm selection criteria also included an intra-storm period of no less than 8 hours and inter-storm no more than 24 hours. Once individual storm events were identified by discharge peaks, the cumulative precipitation amount for the discharge peak day and the two days prior were summed. Half-hourly discharge data were collected at the beginning of the rising curve of the hydrograph until discharge values returned to the initial state before the storm. Corresponding turbidity values were also collected for the same timeframe every 30 minutes. Storms were identified for all selected stations beginning in October 2008 and ending in May 2017. Storms identified were also separated by season, where storms occurred during October and November were classified as early wet season; December to February was mid wet season, and March to May was the late wet season.

2.2 Hysteresis Models

According to hysteresis methods in previous studies, hysteresis models can quantify by indices to assess the difference in hysteresis loop shape and direction at multiple time and space scales. Usually, hysteresis loops exhibit either circular, eight-shaped, linear, or scatter behavior for discharge and turbidity [1, 2]. In this study, we borrowed the methods from Lawler (2006) due to its ability to calculate the hysteresis index at multiple increments and averaging them to obtain a dimensionless HI and also by interpolating turbidity values at the mid-point stream flow of each event. The advantage of using this method is that hysteresis results allow model users to conduct a robust statistical test and compare storm loop for different events at different sites. We first normalized turbidity and discharge values using Eq. (1) and (2) so the different magnitude of storms can be compared.

$$Normalized\ Q_i = \frac{Q_i - Q_{min}}{Q_{max} - Q_{min}} \quad (1)$$

$$Normalized\ TU_i = \frac{TU_i - TU_{min}}{TU_{max} - TU_{min}} \quad (2)$$

Where Q_i and TU_i represent the time step discharge and turbidity, and Q_{max}/TU_{max} and Q_{min}/TU_{min} represent the maximum and minimum of discharge and turbidity (Lloyd et al. 2016a). Then we used the raising limb turbidity values to subtract the falling limb values and obtain the hysteresis index (HI). Positive HI indicates clockwise hysteresis loop, whereas negative HI indicates anticlockwise loop. We defined hysteresis loop into eight classes according to methods by Zuecco et al. (2016). The figure of eight loop patterns when the direction of the hysteresis loop shifts directions during the middle of the high discharge event. Hysteresis index for each storm events was calculated after classifying loops using the derived equation from Lloyd *et al.* (2016) and Zuecco *et al.* (2016) in Eq. (3)

$$HI = TU_{RL\_Norm} - TU_{FL\_Norm} \quad (3)$$

where *HI* represents the hysteresis index, computed with the rising limb (RL_Norm) and falling limb (FL_Norm) of normalized turbidity using javascript developed by Zuecco *et al.* (2016). We examined the temporal variability of hysteresis index and loop patterns by season and looked for spatial variability across all four studied stations.

2.3 Statistical Models

Spearman's rank non-parametric correlation model was used to compare discharge, turbidity, and precipitation variables for each identified storm in R v. 3.5.1 (R Core Team 2013). Variables compared were discharge maximum, minimum, and range; turbidity maximum, minimum, and range; hysteresis index, and 3-day cumulative precipitation. Correlation coefficients for storms in each studied station were calculated on two different time scales (water year and season). P-values of each correlation test was examined to evaluate the statistical significance. For turbidity and discharge variables, the positive logarithmic relationship has been observed in previous studies [3–6] between sediment concentration and discharge. Since turbidity measurements were found to be highly correlated to sediment concentration and reliable to approximate suspended sediment concentration [7, 8], we used log-transformed turbidity values to construct similar regression with log-transformed discharge in SPSS 23 (IBM Corp. 2017). For other variables, the regular linear regression models were used to test the contribution of each independent variables and their ability to predict the dependent variables. Rating curve and linear regression line slope equation were calculated along with the coefficient of determination (R^2).

3. Results

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	SUM
2009	-	56	53	209	42	3	3	85	3	-	-	-	451
2010	-	-	50	35	-	62	18	3	72	4	-	-	243
2011	-	-	186	54	-	-	-	-	-	-	-	-	240
2012	-	38	75	274	21	140	85	1	10	14	-	-	656
2013	18	95	73	15	-	23	18	-	-	-	1	24	264
2014	30	1	49	-	205	223	8	10	1	-	-	-	525
2015	1	28	76	31	-	-	-	-	-	-	-	-	135
2016	-	30	125	-	2	-	-	-	-	-	-	-	157
2017	-	-	-	-	80	51	3	-	-	-	-	-	133
SUM	49	246	685	616	349	500	133	98	85	18	1	24	2801

Table C1. Number of hours turbidity values exceeded 10 FNU each month from WY 2009-2017

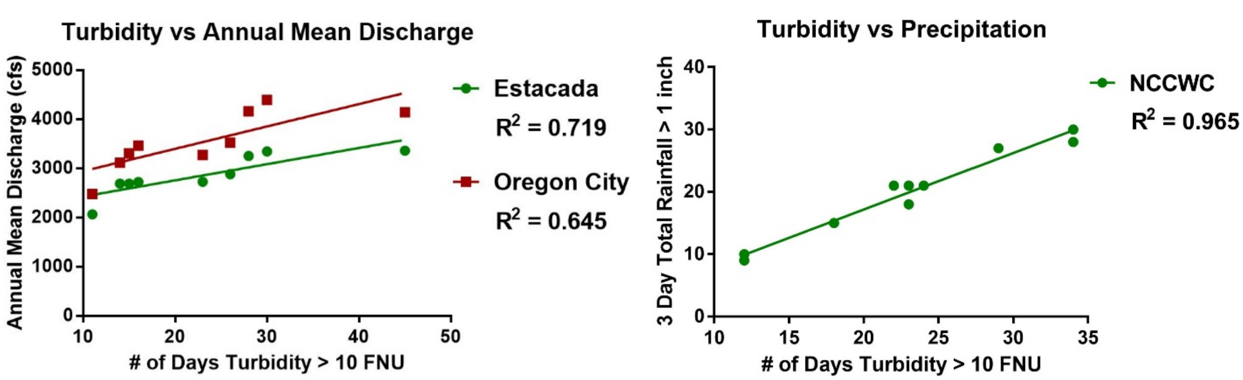


Figure C1. Correlation between number of days when turbidity values exceeded 10 FNU, annual mean discharge, and 3-day cumulative precipitation

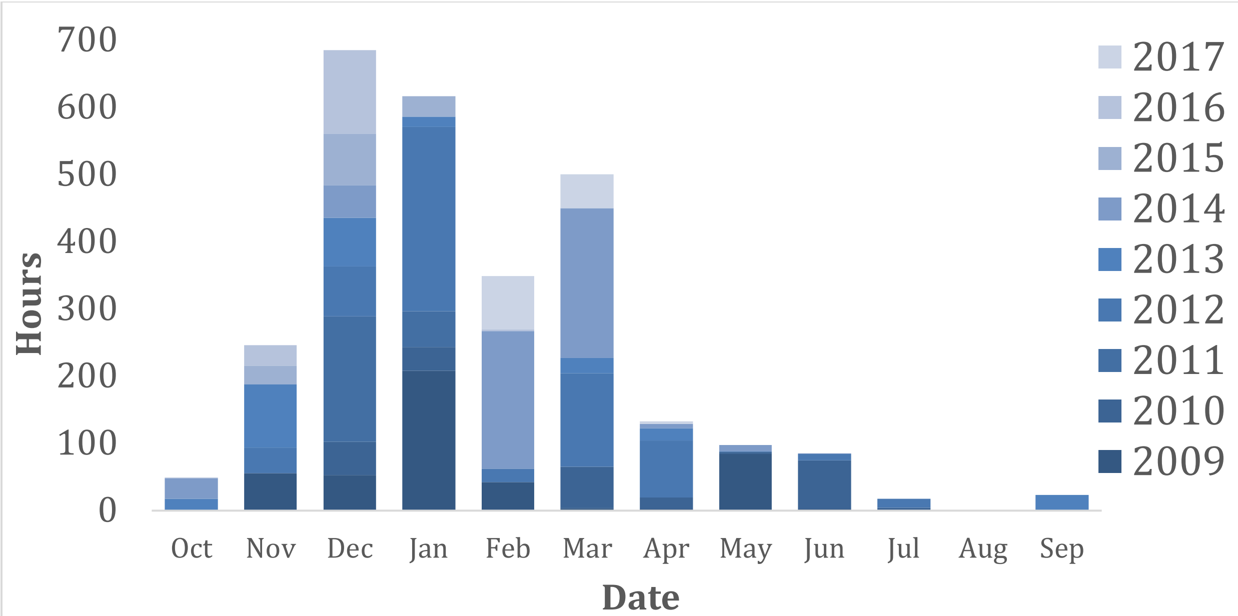


Figure C2. Number of hours where turbidity exceeded 10 FNU each month from WY 2009-2017

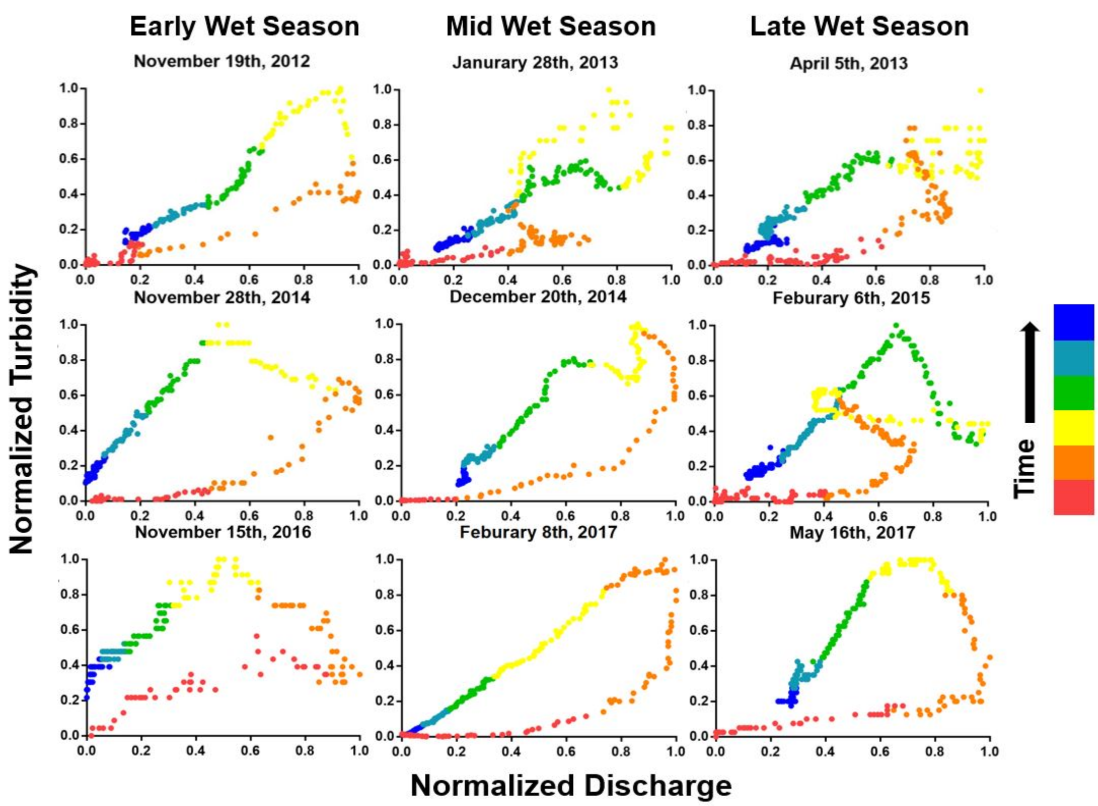


Figure C3. Selected storms hysteresis in water year 2013, 2015, and 2017 at Estacada

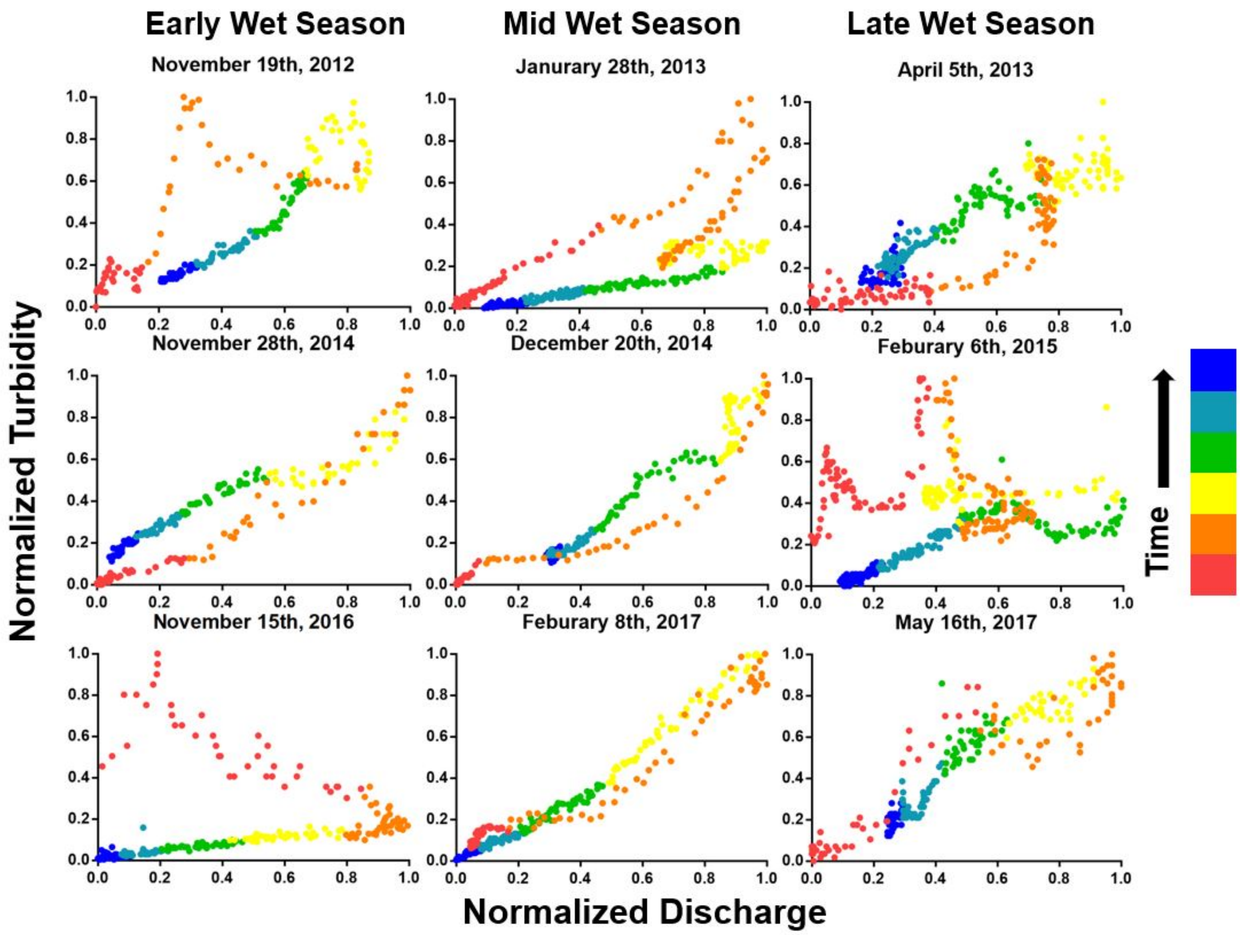


Figure C4. Selected storms hysteresis in water year 2013, 2015, and 2017 at Oregon City

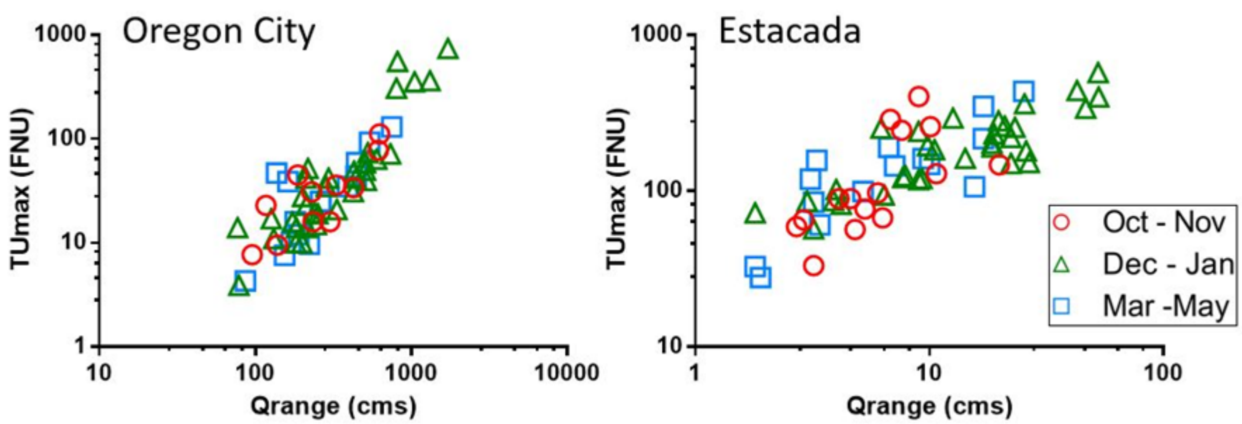


Figure C5. Log Discharge range and turbidity maximum rating curves by nonlinear regression model at studied sites; n=59 (Oregon City & Estacada)

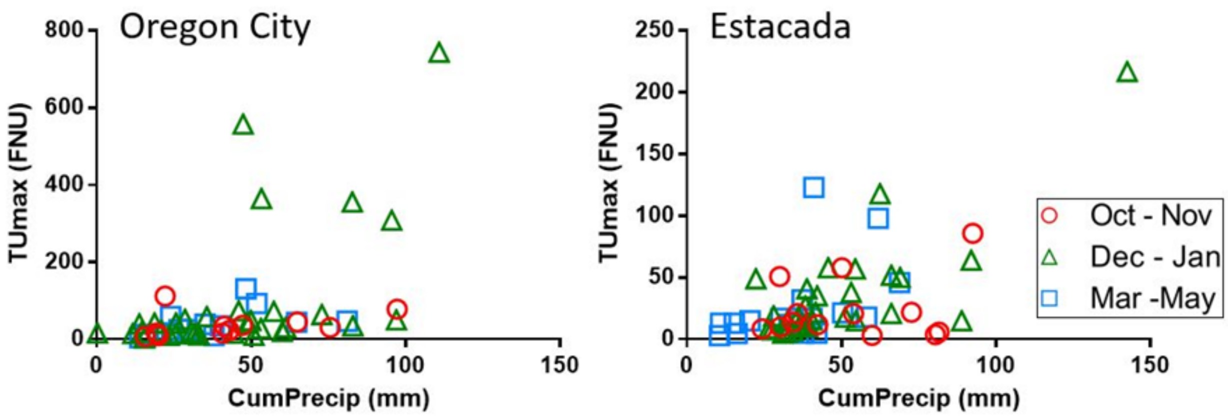


Figure C6. Linear regression models of turbidity maximum and cumulative precipitation for study sites; n=59 (Oregon City & Estacada)

Table C2. Summary of annual discharge, turbidity, and precipitation values at Estacada and Oregon City

	Estacada		Oregon City		NCCWC Turbidity	
Water Year	Annual Mean Discharge	Annual Mean of Daily Turbidity Max	Annual Mean Discharge	Annual Mean of Daily Turbidity Max	# of Days > 10 FNU	# of Storms Identified
2009	2727	7.64	3274	10.72	23	6
2010	2689	5.93	3113	5.05	14	6
2011	3360	6.23	4139	12.34	45	3
2012	3253	10.46	4159	13.56	28	8
2013	**2689**	**5.28**	**3305**	**6.17**	**15**	**8**
2014	2880	6.37	3525	6.58	26	11
2015	**2063**	**2.88**	**2483**	**4.95**	**11**	**5**
2016	2723	2.95	3460	6.44	16	6
2017	**3343**	**2.97**	**4394**	**7.41**	**30**	**13**

Table C3. Spearman's rank correlation coefficients values by study sites and season (*significant at the 0.1 level; ** significant at the 0.05 level; n=sample size). Highest correlation coefficient values are shaded for each location.

Station	Discharge & Turbidity			Turbidity & Precipitation		
	Oct - Nov	Dec - Feb	Mar - May	Oct - Nov	Dec - Feb	Mar - May
Oregon City	0.73*	0.89**	0.68**	0.65*	0.56**	0.72**
	(n=11)	(n=33)	(n=15)	(n=11)	(n=33)	(n=15)
Estacada	0.91**	0.71**	0.84**	0.22	0.63**	0.67**
	(n=13)	(n=30)	(n=16)	(n=13)	(n=30)	(n=16)

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