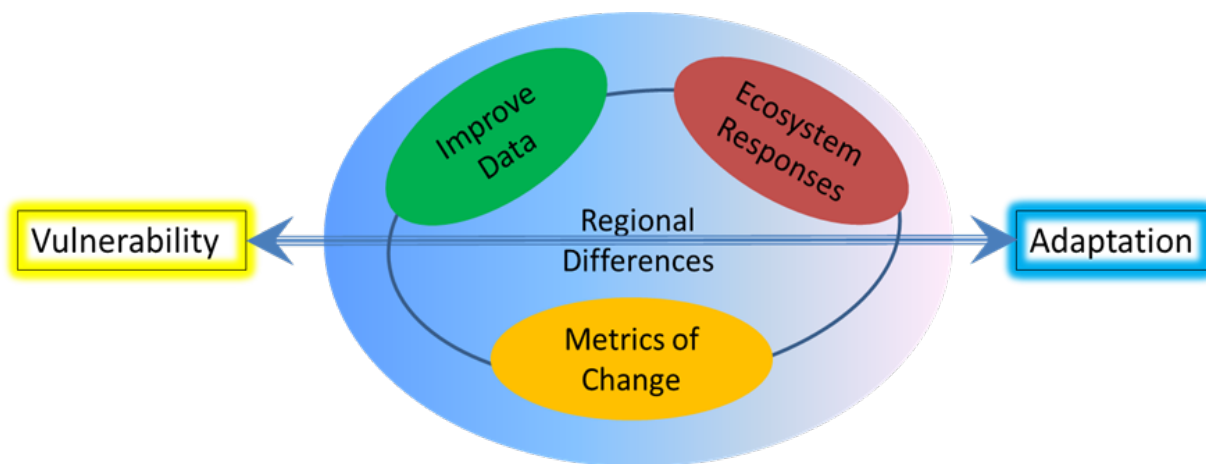




Office of Research and Development, National Air and Energy Program,
Climate Impacts and Vulnerability Assessments, Project 2:

Climate Impacts on Watersheds, Water Quality, and Ecosystems Project (CIVA-2)

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Introduction

Project Lead: Peter. A. Beedlow

Climate change poses unique challenges for protecting environmental resources upon which our society depends. Understanding climate change impacts on water quality, watersheds, ecosystems, and constituent species is critical for societal adaptation, including sustaining environmental goods and services. Further, it is essential for achieving the mission of the United States Environmental Protection Agency (EPA) to protect human health and the environment, now and into the future.

Adapting to changing climate hinges on knowing the regional and local vulnerabilities and impacts to water resources and ecosystem services. Variations in risk result from differences in exposure (i.e., changes in climate-related stressors), sensitivity (i.e., degree to which the system is affected), and the underlying adaptive capacity (i.e., ability to adjust) of ecosystems. Determining social and ecological risk is a major challenge because of insufficient data, knowledge and models, including uncertainties about the regional and seasonal nature of changing climate and how water, watersheds and associated ecosystem services respond to interacting biological and physical stressors.

Research conducted by the EPA's Office of Research and Development (ORD) under the Air, Climate and Energy Program addressed essential and innovative science and engineering needed to address climate change and improve air and water quality⁴. This report is a summary of research results from tasks within the *Climate Impacts and Vulnerability Assessments: Impacts on Watersheds, Water Quality, and Ecosystems Project* (CIVA-2).

The CIVA-2 research was directly responsive to the needs of our partners: OW, the National Water Program Climate Strategy, and individual Regions. This project supported the Agency's targeted adaptation actions by providing the means to measure and monitor risk from changing climate to watersheds, water quality, ecosystems and economically important species across geographical regions. Importantly, the research furthered the ability to account for potential climate change effects on OW water programs. Specific program needs addressed in this project have been identified from OW priorities for climate change and water research in support of the National Water Program Climate Change Strategy.

The focus of CIVA-2 was to understand key aspects of ecosystem, watershed, and water quality vulnerability to changing climate and to inform adaptation efforts. Here, adaptation refers to human actions to support adjustments in natural or human systems to a new or

⁴ U.S. Environmental Protection Agency. 2015. Air, Climate, and Energy Strategic Research Action Plan 2016-2019. EPA 601/K-15/005. 34 pp, 3 MB. https://www.epa.gov/sites/production/files/2015-10/documents/strap_2016 ace 508.pdf

changing environment that exploit beneficial opportunities or moderate negative effects. Our objectives were to improve data, understand ecosystem responses and develop metrics of change, which will allow us to identify potential impacts and develop adaptation strategies at regional and local scales (Figure 1). Results of this multi-faceted research support national, state and local governments, as well as non-governmental entities in promoting resilience by identifying characteristics of populations, watersheds and ecosystems that are susceptible to the direct and indirect effects from changing climate.

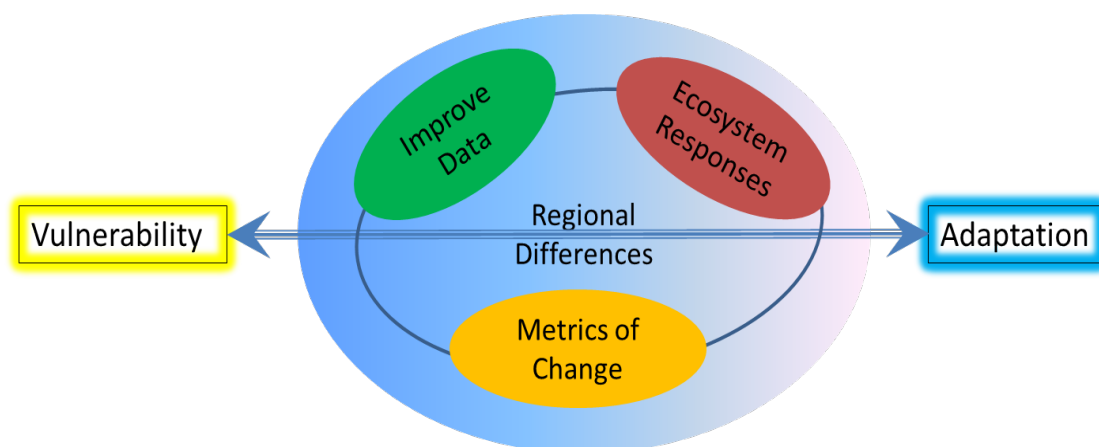


Figure 1. Successful adaptation requires realistic evaluation of vulnerabilities to climate change at manageable scales, i.e., watersheds. Similarly, vulnerabilities may change as adaptation strategies are implemented. So, it is necessary to evaluate vulnerabilities and adaptation strategies over time. To do this we need a) *improved data*, both physical and biological, at watershed scales, b) better models of *ecosystem responses* to changes in seasonal climate and disturbance regimes, and c) *metrics of change* so that *adaptation* strategies and changing *vulnerability* can be assessed. Moreover, to establish national policies for protecting water resources and related ecosystem services, we must be able to account for regional differences in vulnerabilities and adaptation success.

Working with partners, scientists in CIVA-2 investigated the impacts of changing climate on inland watersheds and near-shore environments, the ecosystem components and processes inherent to those systems, and the provisioning of ecosystem services (particularly water resources) received from those ecosystems. The findings are presented by task and emphasize peer reviewed research published in scientific journals and agency reports. The summaries in this report are not intended to provide details of the various research activities, but rather are intended to point the reader toward the published material. At the end of each task summary is a list of “publications resulting from this research.” Publications dated 2016-2019 are from the current planning cycle; those dated 2012-2015 are from the previous cycle. Some CIVA-2 tasks span both cycles while others were only in the most recent.

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Task Title: CIVA-2.1 – Assessing impacts of individual and multiple climate stressors on near-coastal species at a regional scale

Task Lead: Christina L. Folger and Henry Lee II, ret.

Task Description

The overall objectives of the research were to 1) develop a practical framework to predicting the relative vulnerability of near-coastal species to individual and multiple climate stressors at regional scales, 2) identify the primary climate stressors impacting specific species and habitats and how risk varies geographically, and 3) use these predictions to inform regionally-specific conservation and adaption strategies, including developing geographically-specific climate indicators. A related objective was to develop a web-based decision tool, the Coastal Biodiversity Risk Assessment Tool (CBRAT; <http://www.cbrat.org/>) for EPA and state managers, as well as to serve as a research and public outreach tool. This summary includes related research conducted under the previous research cycle: ACE 018 – “Vulnerability of Near-Coastal Species and Habitats to Individual and Multiple Climate Drivers at Regional Scales.”

Background

With projected increases in air and ocean temperatures, reductions in ocean pH (ocean acidification), and increasing sea level rise, climate change is arguably the greatest environmental threat facing near-coastal species. Over the next 20 to 100 years, climate change will likely affect both species diversity and the ecosystem services they provide. Many nearshore (0-200m depth) marine species, crab and shellfish, support multi-million-dollar aquaculture business and wild commercial fisheries from Southern California to the Bering Sea, e.g., oysters alone support a \$270 million aquaculture industry in the U.S. Pacific Northwest; crab harvesting in the Bering Sea generates approximately \$390 million in wholesale revenues annually. Additionally, recreational shellfish harvesting generates millions of tourism dollars annually, thereby providing much needed economic opportunities for rural coastal communities. Near shore species will vary in their vulnerability to specific climatic changes and therefore, climate impacts will also vary geographically. To allow resource managers to focus on the species and locations at greatest risk, it is critical to have a basic knowledge of the extent and pattern of climate risk.

We conducted climate risk analyses on all the crabs (417 species), bivalves (892 species) and rockfish (71 species) that occur in the ten marine ecoregions spanning the Southern California north along the West Coast of North America to the Beaufort Sea in the Arctic. How will such economically and ecologically important species react to changes in oceanic and environmental changes? Our objective was to create an organized schema that predicts which

species are most vulnerable to climate change, how vulnerability changes geographically along the coast, and what climate drivers are most likely to impact specific species.

Approach

To address these needs, we developed a rule-based framework that predicts the relative risk of near-coastal species to warming ocean temperatures, ocean acidification, and sea level rise at regional scales. The algorithm predicting risk evaluates over thirty aspects of a species' life-history attributes, biogeographic abundance patterns, and taxon-level sensitivities to temperature increases, sea level rise, and ocean acidification to generate first-order vulnerability projections. This framework is executed in the form of an online tool, the Coastal Biodiversity Risk Analysis Tool, CBRAT (<http://www.cbrat.org/>). CBRAT uses a "hybrid" approach to estimate relative abundances integrating regional and local quantitative survey data, natural history texts, expert opinion, and online biodiversity databases (Figure 1). The source of climate data varied; for the temperature analysis historic SSTs were derived from an analysis of 28 years of "advanced very high-resolution radiometer" remote sensing data while the future projections were extracted from the CMIP5 model served through NOAA's Climate Change Web Portal. "Habitat thresholds" used for the sea level rise analyses were compiled from the literature and SLR models. Both the historic mean sea surface pH values and the predicted sea surface pH values are from the CMIP5 model downloaded from NOAA's Climate Web Portal. Aragonite saturation state projections were derived from published literature. Full methods are provided in Lee et al. 2017a.



Figure 1. General flow of data into and out of CBRAT. Output is displayed in spreadsheet form.

A key feature of the CBRAT web-tool is that managers and researchers can easily evaluate different climate scenarios and assumptions by changing the baseline or future climate values and/or the effects thresholds for temperature, ocean acidification, and sea level rise. CBRAT outputs all the biotic trait information for each species (e.g., abundance, preferred habitat, depth preferences) as well as the risk associated with each rule for each species by ecoregion. This output allows users to evaluate the details of risk patterns as well as use the synthesized biotic trait for other types of analyses.

Findings

Using the online web tool CBRAT.org, the framework can predict: A) climate risks for rare species as well as for better studied economically important cultured or commercially harvested species; B) how risk changes under different climate scenarios; C) which species are likely to migrate northward under future environmental conditions; D) geographic patterns of importance for different climate stressors. This overview presents some of the questions that can be addressed with CBRAT and a subset of the results.

A. How many economically important bivalves/shellfish may be at risk under changing environmental conditions? How does that change by ecoregion?

Sea level rise, warming ocean temperatures, and acidification are expected to change the abundance and distribution of many ocean and estuarine species. Consequently, the beneficial ecosystem services bivalves provide are also at risk. Shellfish (e.g., oysters, clams and mussels) aquaculture is a major job creator and economic driver for small coastal communities in the U.S. Recreational clamming also brings in thousands of tourist dollars annually to Pacific Northwest and Alaska rural communities. Commercial fisheries targeting wild scallops, wild geoducks, and other wild bivalves are million-dollar industries. To evaluate which economically important species will be most impacted by changing environmental conditions, we evaluated risk from each climate stressor for all the bivalves/shellfish species either cultured, harvested or recreationally caught in each of the ten ecoregions in our area of focus.

Puget Sound/Georgia Trough, the Oregonian, and Fiordland ecoregions utilize the highest number of bivalve species across the three harvest categories, consequently, they will be the most financially and ecologically impacted when services decline. Ocean acidification was the primary driver for bivalve risk and accounted for 98% of the 'At-Risk' species.

Although ocean acidification is projected to be magnified in the colder northern oceans, e.g., Beaufort, Chukchi, and Bering Seas, the impact on bivalves will be less due to the low number of endemic bivalve species present and the absence of aquaculture and limited harvesting in those ecoregions. Figure 2. represents the number of economically important shellfish species that are at high, moderate or low risk to predicted changes in either sea level rise, increasing ocean temperatures or ocean acidification.

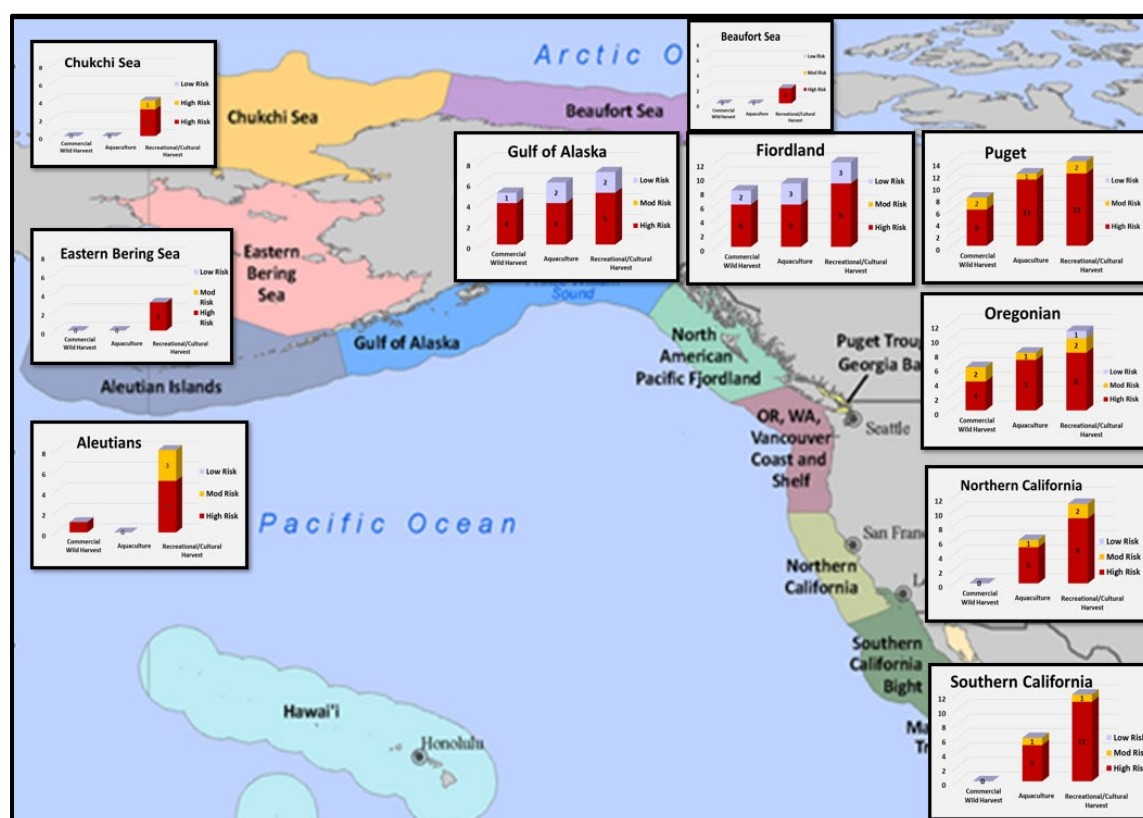


Figure 2. Number of economically important bivalves at low, moderate or high risk under RCP 8.5 for three use categories in each ecoregion. Use categories include: Wild Commercial Harvest, e.g., scallop fishery; Aquaculture, e.g., oyster cultivation; and Recreational/Tribal Harvest, e.g., razor clamming.

B. How will a species' risk change under two different emissions scenarios: RCP 8.5 and RCP 4.5?

Species specific findings are too numerous to present here, however Figures 3-6 from the Risk Analysis Case Study, Lee et al., 2017b, show the percentage of species in each taxa group that will experience high to moderate overall risk by the year 2100 under two future climate scenarios (RCP 8.5, the business as usual scenario and RCP 4.5, a reduced emissions scenario). Results indicate a substantial decrease in the number of ecoregions with species at high risk under RCP 4.5 compared to RCP 8.5. However, there is no consistent geographical pattern in risk reductions at the ecoregion scale. Across the four taxa, *Brachyura* crab (e.g., Dungeness crab), *Lithodoidea* crab (e.g., King & Snow crab), bivalves, and rockfish. The model predicts no reduction in risk in some ecoregions with RCP 4.5 while predicting substantial declines in others.

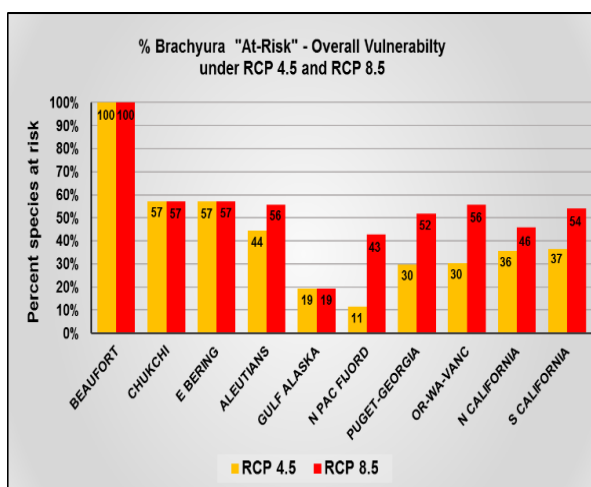


Figure 3. Percent of Brachyura/ 'True Crabs', e.g., Dungeness crab 'At-Risk' with RCP 4.5 and 8.5 scenarios.

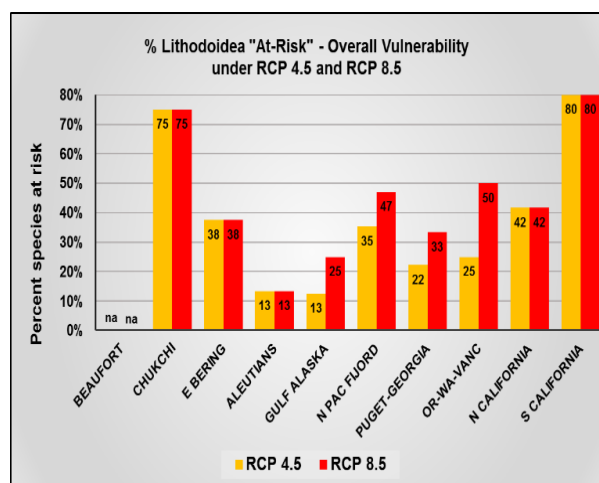


Figure 4. Percent of Lithodid/Spider crabs, e.g., King crabs, 'At-Risk' with RCP 4.5 and 8.5 scenarios.

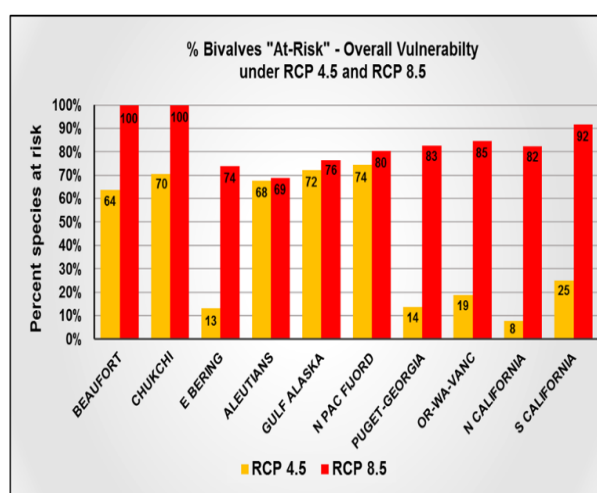


Figure 5. Percent of all bivalve species 'At-Risk' under RCP 4.5 and 8.5 scenarios.

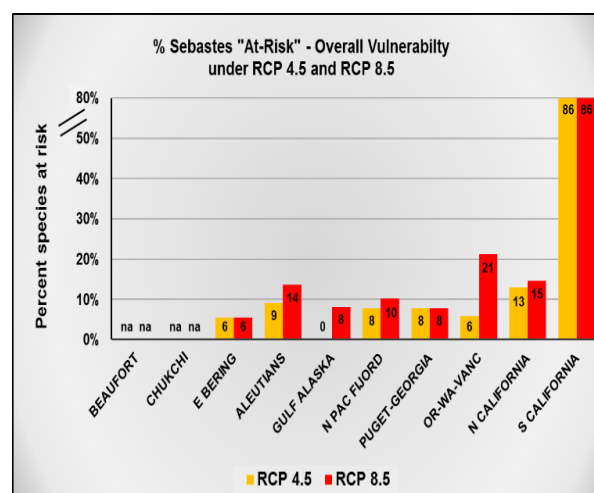


Figure 6. Percent of Sebastes/Rockfish, 'At-Risk' with RCP 4.5 and 8.5 scenarios.

C. Which species are likely to migrate northward under future environmental conditions?

We were also able to evaluate patterns of northern colonization as southern species migrate northward into waters previously too cold to inhabit (Figure 7). As with the risks, this model predicts no consistent geographical pattern in the reduction of northern colonists per ecoregion. However, when summed over the ten ecoregions, the model predicts the total number of potential colonists to be moderately to substantially reduced under the RCP 4.5 scenario, depending upon the taxon.

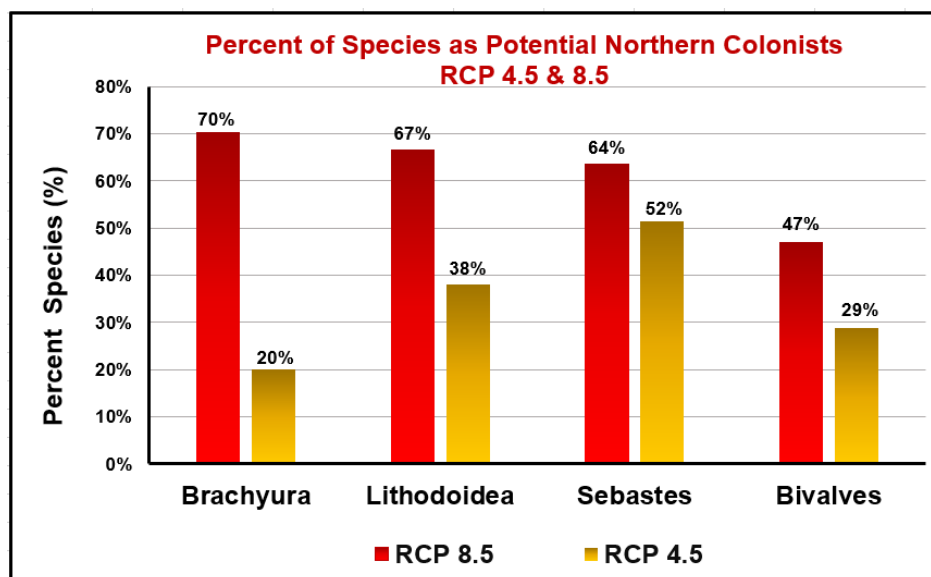


Figure 7. Percent of species identified as possible northern colonists (e.g., species that currently can live within the thermal range of the *projected* water temperatures to the ecoregion to the north.) Analyses included the U.S. Arctic and North Eastern Pacific ecoregions under RCP 4.5 (yellow) and RCP 8.5 (red).

D. Which environmental stressors are most influential? How do those stressors vary geographically?

The influence of individual climate stressors (ocean temperature, sea level rise, and increased pH) varies. Sea level analyses indicated strong geographical patterns of risk; with minimal impacts of sea level rise in the north (Alaska) and greater risk along the southern coast of North America. The lack of risk in the northern ecoregions is due to high isostatic uplift countering SLR in much of Alaska and the paucity of certain intertidal species in the Arctic. In general, species that occupy intertidal habitat will experience the most impact from a rising sea level while deeper subtidal species will experience fewer impacts from rising sea levels.

Temperature analyses show geographic patterns of higher thermal risks in the southernmost occupied ecoregions and decreased risk in a species' northernmost ecoregions. The lack of substantial thermal impacts in the more northern range of a species assumes either that warm-tolerant genotypes occur in ecoregions north of the warmest occupied ecoregion or that warm-tolerant genotypes from southern ecoregions migrate northward.

When gaseous CO₂ dissolves in seawater, it forms a weak acid; this process, known as acidification, decreases the saturation state of aragonite (Ω arag) and calcite (Ω cal), the two mineral forms of calcium carbonate that most bivalves use to form their shells. Coastal water off the Pacific Northwest with Ω arag saturation values less than 2.0 are already common throughout the spring and summer leading to major declines in oyster larvae production. In our analyses, the percentage of bivalves at moderate or high risk, e.g., 'At Risk', ranged from 73% in the North American Fjordland (north coast of British Columbia, CA) to 100% in most other ecoregions. The exception being the Arctic ecoregions where there are no commercial or recreationally important bivalves. Figure 8 illustrates the percent that each climate or natural history stressor influenced the overall vulnerability rating for bivalves. Ocean acidification had the most influence, followed by sea level rise, natural history traits (e.g., distribution, symbiont, breeding strategy), and ocean temperature. Influence of stressors will vary geographically and by taxon.

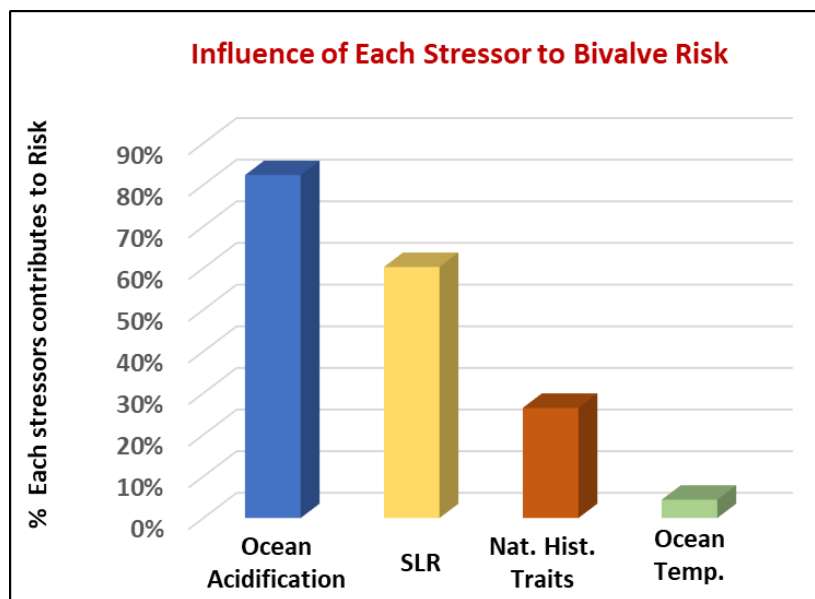


Figure 8. Percent that each stressor contributed to the overall determination of risk for bivalve/shellfish species.

Conclusions

In a 2018 report by The Oregon Coordinating Council on Ocean Acidification and Hypoxia, scientists outline research needs and priorities to help resource managers and policy makers prepare for significant changes facing West Coast fisheries and aquaculture. A priority recommendation from the report is the need to develop tools to identify which marine species are most vulnerable to ocean acidification and other environmental conditions with a focus on commercially, recreationally, culturally, and ecologically important species. Although uncertainties always exist, tools such as the Coastal Biodiversity Risk Analysis Tool (CBRAT) can provide researchers and planners with specific information that will allow for a focused

approach to adaptation and resilience strategies. While predictions are sufficient to flag high risk commercial species at a regional scale, they are not intended for fisheries management.

Publications resulting from this research

Coastal Biodiversity Risk Analysis Tool web site: <http://www.cbrat.org/> (The CBRAT website is currently not available as it undergoes updates associated with the migration to EPA servers.)

- Lee II, H., Reusser, D.A., Marko, K.M., and Ranelletti, M. 2012. User's Guide and Metadata for the PICES Nonindigenous Species Information System. Office of Research and Development, National Health and Environmental Effects Research Laboratory, EPA EPA/600/R/12/654.
- Lee II, H. and Reusser, D. A., 2012. PICES Nonindigenous Species Information System. Office of Research and Development, National Health and Environmental Effects Research Laboratory. Microsoft Access database.
- Lee II, H. and Reusser, D. A., 2012. Atlas of Nonindigenous Marine and Estuarine Species in the North Pacific. Office of Research and Development, National Health and Environmental Effects Research Laboratory, EPA/600/R/12/631.
- Lee II, H, Reusser, D.A., Marko, K.M., Folger, C.L., Graham, R., Loiselle, R., Saarinen, E.V., Frazier M.R., and Clinton, P.J. 2013. Crabs in Crisis and Stressed Sebastes: Framework for Assessing the Vulnerability of Nearshore Species and Habitats to Climate Change. U.S. EPA, Office of Research and Development, National Health and Environmental Effects Laboratory, Western Ecology Division. EPA Report 600/
- Lee II, H., Marko, K., Hanshumaker, M., Folger, C., and Graham, R. 2015. User's Guide & Metadata to Coastal Biodiversity Risk Analysis Tool (CBRAT): Framework for the Systemization of Life History and Biogeographic Information. EPA Report. EPA/601/B-15/001. 123 pages.
- Lee II, H., Folger, C.L. Reusser, D.A., Clinton, P. and Graham, R. 2017a. Predicting Patterns of Vulnerability to Climate Change in Near Coastal Species Using an Algorithm-Based Risk Framework. EPA/ORD/R-17/052. 297 pages.
- Lee II, H., Folger, C.L. Reusser, D.A., Clinton, P. and Graham, R. 2017b. Risk Analysis of Near-Coastal Species of the U.S. Pacific Coast: Case Study Comparing Risks Associated with Two Future Climate Scenarios. EPA/600/R-17/351. 61 pages.

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Task Title: CIVA-2.2 – National Vulnerability Assessment Methods Applied to Wetlands

Task Lead: Jordan West

Task Description

This task focused on vulnerability and adaptation assessment methods for wetlands, in support of EPA's mission and responsibilities as defined by the Clean Water Act (CWA). Specifically, it directly supported EPA's Office of Water research needs for addressing watersheds and coastal wetlands at risk. The approaches, analyses, and synthetic products are designed to build the capacity of EPA program and regional offices, water and wetland managers, and other decision-makers to assess and respond to global change impacts on wetland ecosystem processes and services.

Background

Wetlands are known to provide myriad vital ecosystem functions and services, which may be under threat from a changing climate. Inland freshwater wetlands are susceptible to climate change primarily through the effects of changing temperature and precipitation patterns on surface and ground water hydrology, where a variation of only a few centimeters can result in changes in wetland size, loss of wetlands to drylands, and conversions to other wetland types. In the case of coastal wetlands, a primary threat from climate change is accelerating sea level rise (SLR), where greater inundation combined with wave action leads to increased shoreline erosion, greater susceptibility to storm surge with resulting interior wetland erosion and breakup, and the potential for marsh "drowning" (i.e., system collapse). Addressing these challenges is especially difficult because these effects may not be homogenous across wetland types, ecoregions, mesoscale watersheds and ecosystem services, so broad application of the same management techniques may not be appropriate.

To enable integration of relevant climate change considerations into effective management adaptation approaches, a framework is needed to assess sources of variation in climate change vulnerability across wetland typologies as well as across spatial and temporal scales. Thus, the purpose of this project was to (1) develop a "Relative Wetland Vulnerabilities" Framework (RWVF) based on vulnerability assessment methods, resilience theory, and wetlands classifications; (2) demonstrate the framework's applicability for assessing both inland freshwater and coastal wetlands; and (3) illustrate how the results could be used to inform adaptation of EPA OW, Regional and State wetlands programs.

Approach

The first phase of work (Figure 1) involved developing the RWVF via a pilot study, using watersheds in central Pennsylvania as the study area. We deconstructed vulnerability into dimensions of exposure and "sensitivity + adaptive capacity" (or "response") and identified

relevant measures of these as they pertain to wetland extent and plant community composition. As a test of the framework, we populated it with data for three primary hydrogeomorphic (HGM) wetland types (riverine, slope, and depression) in seven small watersheds across four ecoregions (Ridge & Valley, Piedmont, Unglaciaded Plateau, and Glaciaded Plateau) in the Susquehanna River watershed. We used data from the SRES A2 emissions experiment and MRI-CGCM2.3.2 climate model as inputs to the Penn State Integrated Hydrologic Model to simulate future exposures to altered hydrologic conditions in the seven watersheds, expressed as two hydrologic metrics: % time groundwater levels occur in the upper 30 cm (rooting zone) during the growing season, and median difference between spring and summer mean water levels. We then examined the spatial and temporal scales at which the components of vulnerability (exposure and response) showed significant relative differences.

The second phase of work (Figure 2) extended application of the framework to coastal wetlands through a collaboration with the Partnership for the Delaware Estuary. We examined seven salt marsh areas in the Lower Delaware Bay (four in New Jersey and three in Delaware). The Sea-Level Affecting Marshes Model (SLAMM) was used to generate spatially explicit projections of SLR-induced changes in acreage for early- to late-century time periods under three SLR scenarios, and for three different land protection scenarios. We then incorporated the SLAMM results into the RWVF to distinguish varying exposures and responses for each marsh. Because the concept of vulnerability depends on what ecosystem service/management objective is at play, we not only assessed changes in total salt marsh habitat, but also broke salt marshes into high and low marsh zones. We then explored vulnerabilities in the context of three different management examples, centered on preservation of: (1) saltmarsh sparrow nesting habitat (high marsh), (2) blue crab nursery habitat (low marsh), and (3) flood protection (total marsh).

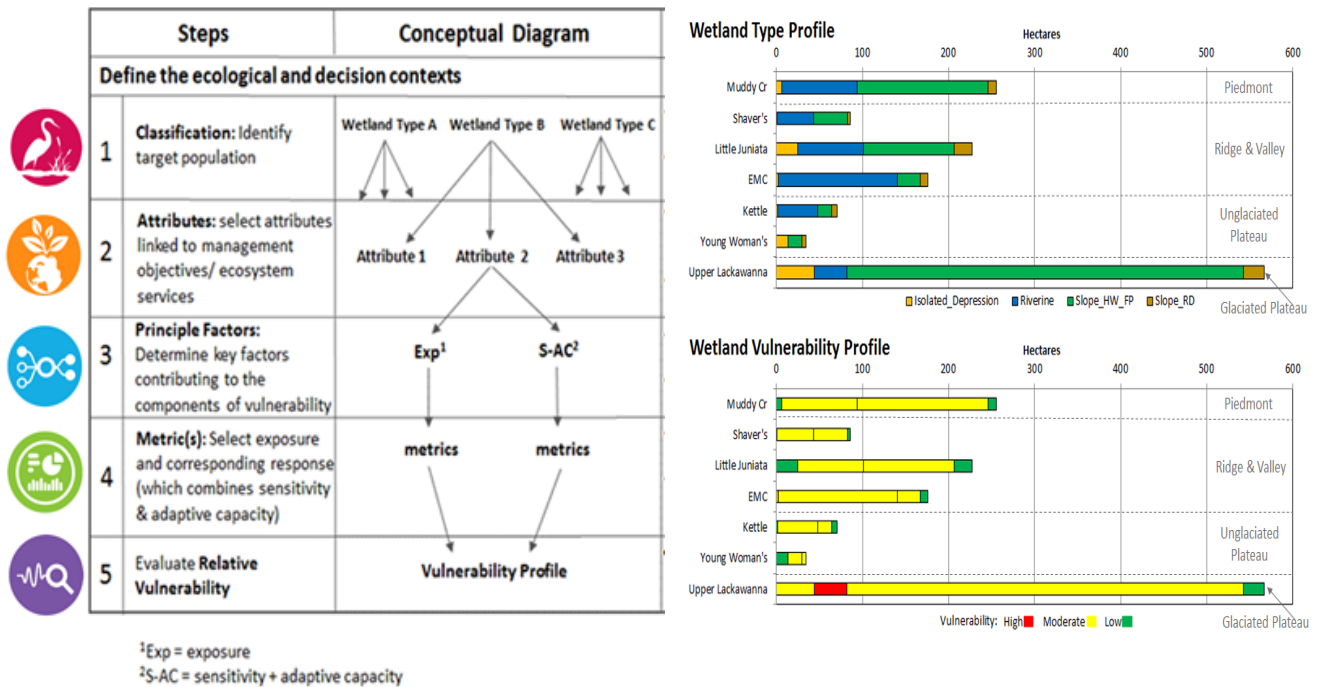
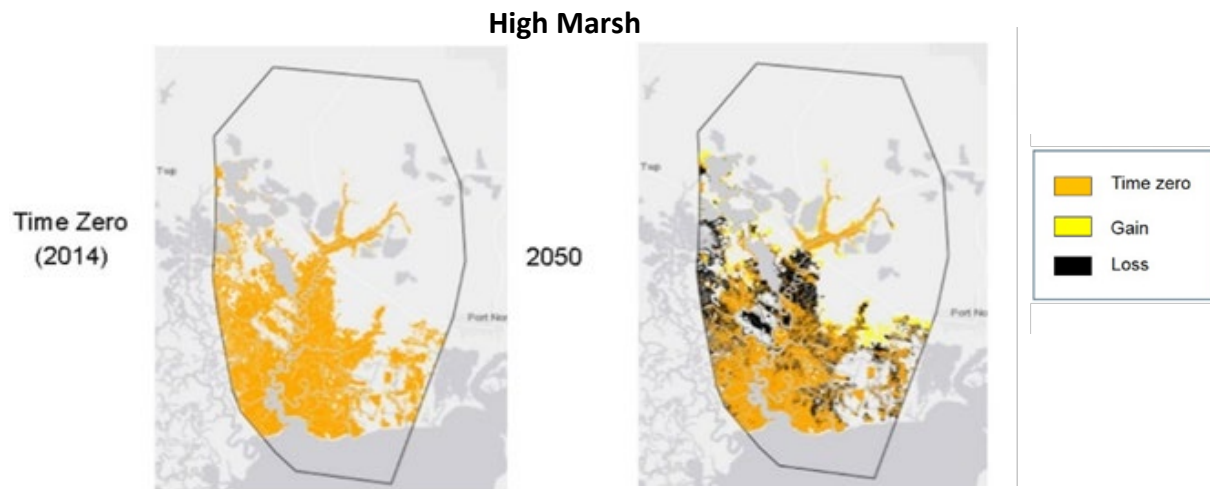


Figure 1. The Relative Wetland Vulnerabilities Framework (left) was developed using seven watersheds (right) in central Pennsylvania as a pilot region. The framework process focused on three freshwater wetland types (with slope wetlands further divided into headwater floodplain and riparian depression categories) (see acreage distributions at upper-right) and produced profiles of relative vulnerabilities across the seven study watersheds (lower-right) for attributes such as plant community composition (shown in this example). (Wardrop et al. 2019)



	Exposure	High marsh			Low marsh		
		Response			Response		
	Global mean SLR by 2050* (m)	Time zero (acres)	2050 (acres)	% Change	Time zero (acres)	2050 (acres)	% Change
Broadkill	0.34	3239.7	2521.8	-22.2	3955.8	5907.4	49.3
Dennis		9152.5	9206.5	0.6	421.6	939.3	122.8
Dividing		5026.6	3820.8	-24	1707.7	3121.5	82.8
Maurice		5225.4	4926.7	-5.7	1299.5	1899.9	46.2
Mispillion		4261.6	4152.6	-2.6	7165.8	9188.7	28.2
Reeds		3515.5	3528.3	0.4	235.0	467.0	98.7
St Jones		1518.8	1563.2	2.9	1865.2	2102.1	12.7

Figure 2. Top: example from Dividing Creek, New Jersey, of a high marsh gain-loss map generated by the SLAMM modeling effort (U.S. EPA 2019). Bottom: results from the framework application for salt marshes in the Delaware Estuary (Stamp et al. submitted), showing percent change in high and low marsh by mid-century under the intermediate SLR scenario (1-m by 2100). Red color coding indicates acreage loss while green color coding indicates acreage gain. Depending on the priority management target (e.g., sparrows that nest in high marsh or blue crabs that forage in low marsh), the different relative vulnerabilities among sites may have implications for prioritization of sites for protection or restoration.

Findings

In phase one (Figure 1), the RWVF developed for inland wetlands in Pennsylvania showed that relative differences in exposure persist at a very fine spatial grain, exhibiting high variability even among individual watersheds in one ecoregion (Wardrop et al. 2019). For temporal scale, we found strong seasonal but weak annual relative differences in exposure resulting from a magnification of summer dry-down combined with winter and spring wet periods becoming wetter. Wetlands response showed significant differences among wetland types, but also based on location within a given watershed (Figure 1). A comparison between our anticipated hydrologic alterations under climate change and historical changes in hydrology due to anthropogenic disturbance indicated potential shifts in hydrologic patterns that are far beyond anything that wetlands managers have experienced in the past.

In phase two (Figure 2), the SLAMM simulations projected that all Delaware Bay study sites will experience loss of high marsh acreage by late century and gains followed by loss of low marsh and total marsh acreage (USEPA 2019). Rates of change vary across sites, time periods and SLR scenarios. The conversion/loss of low marsh is projected to occur at a slower rate than conversion of high marsh, as low marshes are assumed to have higher accretion rates since they are inundated more frequently and collect more sediment. Gain/loss maps for high and low marsh reveal complex spatial patterns of acreage increases and decreases for each zone type (see example in Figure 2). In applying the SLAMM results (U.S. EPA 2019) within the RWVF for the salt marsh study sites (Stamp et al. submitted), we assessed the change in extent (acreage) separately for high, low and total marsh to examine the implications for the three different management scenarios (high marsh for sparrow nesting habitat, low marsh for crab nursery habitat, total marsh for flood protection). We found that the different marshes rank differently in relative vulnerability depending on whether the focus is on high, low or total marsh (Figure 2).

Conclusions

The Relative Wetland Vulnerabilities Framework is an effective, consistent, and repeatable framework for assessing relative wetland vulnerabilities. In a management context, the delineation of exposure versus response can help in identifying what aspects of vulnerability can potentially be addressed through human adaptation efforts, promoting a strategic approach to management. Information on which resources are vulnerable helps resource managers identify and prioritize among management targets, while information on why a specific resource is vulnerable informs what could be done to reduce that risk. In the case of our inland wetlands case study, we found that all the wetlands of one type, or all the wetlands in one region, are not necessarily similar in their relative vulnerabilities to climate change. Thus, incorporation of vulnerability information into management decisions must occur at the watershed or wetland type level. In the case of our coastal salt marshes case study, patterns of variability among sites in terms of relative vulnerability rankings were very different depending on what marsh zone was examined, emphasizing that the management objective (if related to zonation) can dramatically affect how the relative vulnerability

information is interpreted and applied. When used with these complexities in mind, relative vulnerability results can support management decisions. Information on which areas are expected to undergo gains, losses or conversions can inform monitoring programs and help with prioritization of sites for protection, restoration and/or controlled transitions.

Publications resulting from this research

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- Wardrop, D.H., A. Hamilton, M. Nassry, J.M. West, and A. Britson. 2019. Assessing the relative vulnerability of wetland types to projected hydrologic regime changes. Ecosphere. <https://doi.org/10.1002/ecs2.2561>

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Task Title: CIVA-2.3 – National Hydrologic Landscape Map and Vulnerability Assessment

Task Lead: Scott Leibowitz

Task Description

Climate change is likely to have significant, long-term implications for freshwater resources. Understanding likely impacts on such resources is critical for the development of mitigation and adaptation strategies. Hydrologic effects of climate change – e.g., changes in magnitude and timing of stream flow – have been investigated at individual river sites using hydrologic models. While such modeling can be done for a limited number of rivers or at low resolution, applying such an approach to the entire continental US at a high resolution is infeasible for two reasons: First, because of the time and data required to calibrate each model. And second, certain data poor areas (e.g., rivers in arid and semi-arid regions and low order, headwater rivers) cannot be modeled because of the lack of calibration and validation data.

Hydrologic classification is an alternative approach that has been applied towards understanding the effects of climate change on freshwater resources. This is based on the concept that hydrologic function (e.g., streamflow response) is the result of hydrologic form (e.g., climate and geology). To this end, hydrologic landscapes (HL) were mapped for the western United States. HL classes were defined by factors that are critical to streamflow, i.e., climate, seasonality, subsurface permeability (previously called aquifer permeability), terrain, and surface permeability (previously referred to as soil permeability). A comparison of baseline (1971-2000) and future simulated (2041-2070) climate and seasonality allowed the change in HL distribution to be mapped and vulnerability of streamflow from climate change to be evaluated.

Background

Subtask 1: Understanding the likely impacts of climate change on aquatic resources is critical for the development of mitigation and adaptation strategies. Numerous studies have examined projected changes in climate and hydrology on regional and national scales. Yet better products and services are needed to enable local communities to plan for and respond to hydrologic change. It is especially important to produce information that provides managers with an understanding of the potential impacts of climate on the resources that they manage. Hydrologic classification has been an important tool for understanding hydrologic systems, based on the concept that function (e.g., streamflow response) is the result of form (e.g., climate and geology). Combining hydrologic classification with future climate projections could be an effective way to identify future areas of concern. Here we used such an approach to evaluate and map stream vulnerability to future climate scenarios.

Subtask 2: Climate fluctuations affect the timing, magnitude, and spatial distribution of precipitation and streamflow across the continent. Stable isotopes are a conservative tracer of hydrologic flows and integrate spatial information about the water's origin. Stable isotopes of precipitation vary spatially, allowing for the creation of isoscapes: a map of the spatial signatures of precipitation. We used isoscapes to help understand how and when water sources are changing within major water bodies in the Pacific Northwest and like with HLs identify hydrologically important parts of the landscape.

Approach

Subtask 1: In previous work, we developed hydrologic landscape (HL) maps for the state of Oregon (Wigington et al. 2013). These maps incorporated information on watershed characteristics that are critical to streamflow and hydrologic function, e.g., climate, seasonality, subsurface permeability, terrain, and surface permeability. Results indicated that the HLs reasonably identified areas with similar hydrologic behavior. Patil et al. (2014) used the Oregon HL maps to evaluate where a simple lumped model accurately predicted daily streamflow. Modeling work by Ebersole et al. (2015) showed that one of the HL climate components was the best predictor of the presence of cold water refugia for salmonids in eastern Oregon tributaries. Leibowitz et al. (2014) combined the Oregon HL classification with temperature and precipitation data from global climate models to examine how the HL classification would change as a result of climate change scenarios. They used this information to demonstrate how stream vulnerability could be assessed.

For the current task, we improved the HL methodology and expanded it to the Pacific Northwest (Oregon, Washington, and Idaho; Leibowitz et al. 2016) and then used it to develop a hydrologic landscape map for the six western states of Oregon, Washington, Idaho, California, Nevada, and Arizona (Fig. 1; Jones et al. submitted). This was done using nationally available datasets for climate, topography, and soils as well as subsurface permeability maps that we produced (Comeleo et al. 2014; Stratton et al. 2016). Jones et al. (submitted) then identified areas where future projections of HL climate components were beyond two standard deviations of historical decadal averages. They combined this information from multiple climate models to develop metrics that could be used to map areas that were

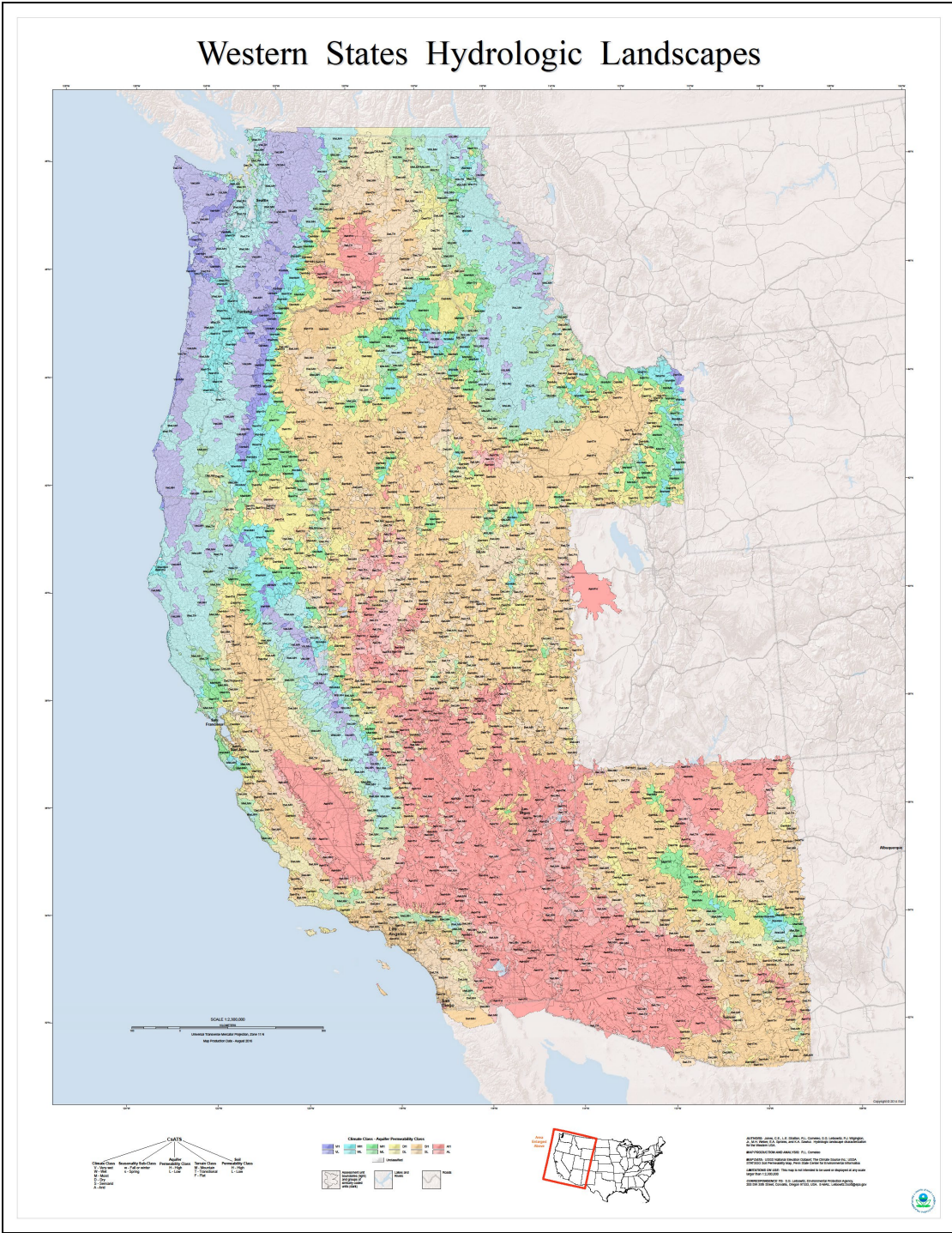


Figure 1. Hydrologic landscape map for the western US states (Jones et al. submitted).

vulnerable to specific hydrologic constraints (e.g., levels of snow pack or available water). In this case, vulnerability refers specifically to the proportion of independent climate projections that exceed two standard deviations of the historical trend.

Subtask 2: In collaboration with the University of Washington, U.S. Forest Service, and the U.S. Geological Survey, we collected water samples and developed isoscapes in basins across four states, including the Willamette (Brooks et al. 2012) and Marys (Nicholas et al. 2017) in Oregon, the Snake in Idaho, the Wenatchee, Snoqualmie, Green, and Skagit in Washington, and the Cowee in Alaska (McGill et al. in review). In the Willamette, Marys, Snake and Snoqualmie Rivers, we collected water samples to develop a time-series of water isotope values to characterize how source waters vary seasonally and annually with varying climate. We developed a technique that can separate the influences of evaporation from source water signals (Bowen et al. 2018), which was particularly important for the Snake River Basin.

Findings

Subtask 1: The resulting maps (Fig. 2) show that temperature and potential evapotranspiration are consistently projected to have high vulnerability values for the western U.S. Precipitation vulnerability is not as spatially uniform as temperature. Most areas with snow are projected to experience significant changes in future snow accumulation. Certain mountainous areas in the West are the most vulnerable to changes in seasonality.

Subtask 2: Elevation is a dominant driver of isotopic variance across these basins, except for the Wenatchee on the east side of the Cascade Range (McGill et al. in review), and the Marys on the east side of the Coast Range (Nicolas et al. 2017). Thus, variation in water isotopes within these west draining rivers could be used to understand how high elevation snowmelt influences the timing and magnitude of streamflow. In the Willamette Basin, we have found that high elevation water contributes the majority of waterflow during the summer low-flow period when demand for water is at its highest (Brooks et al. 2012). The Snoqualmie low-flow is less dependent on high elevation snowmelt (McGill et al. in review). Snowmelt dominates the Snoqualmie in late spring, indicating faster flowpaths for melt water compared to the Willamette. The Cascade snowpack is at risk of disappearing in the future, and low snowpack greatly decreases summer flow even when precipitation amounts are similar across years. In the Marys basin, we found most of the water within the river during summer low-flow originated outside the topographical watershed. Nearly 80% of summer low-flow originates from sandstone and fell as precipitation on the west side of the Coast Range in Oregon (Nicolas et al 2017). In the Snake River, evaporative losses influence flow seasonally, while the source of water feeding the river is restricted to the high mountains in the Grand Tetons except for large snow years, when other mountainous areas also contribute to flow (Windler et al. 2018).

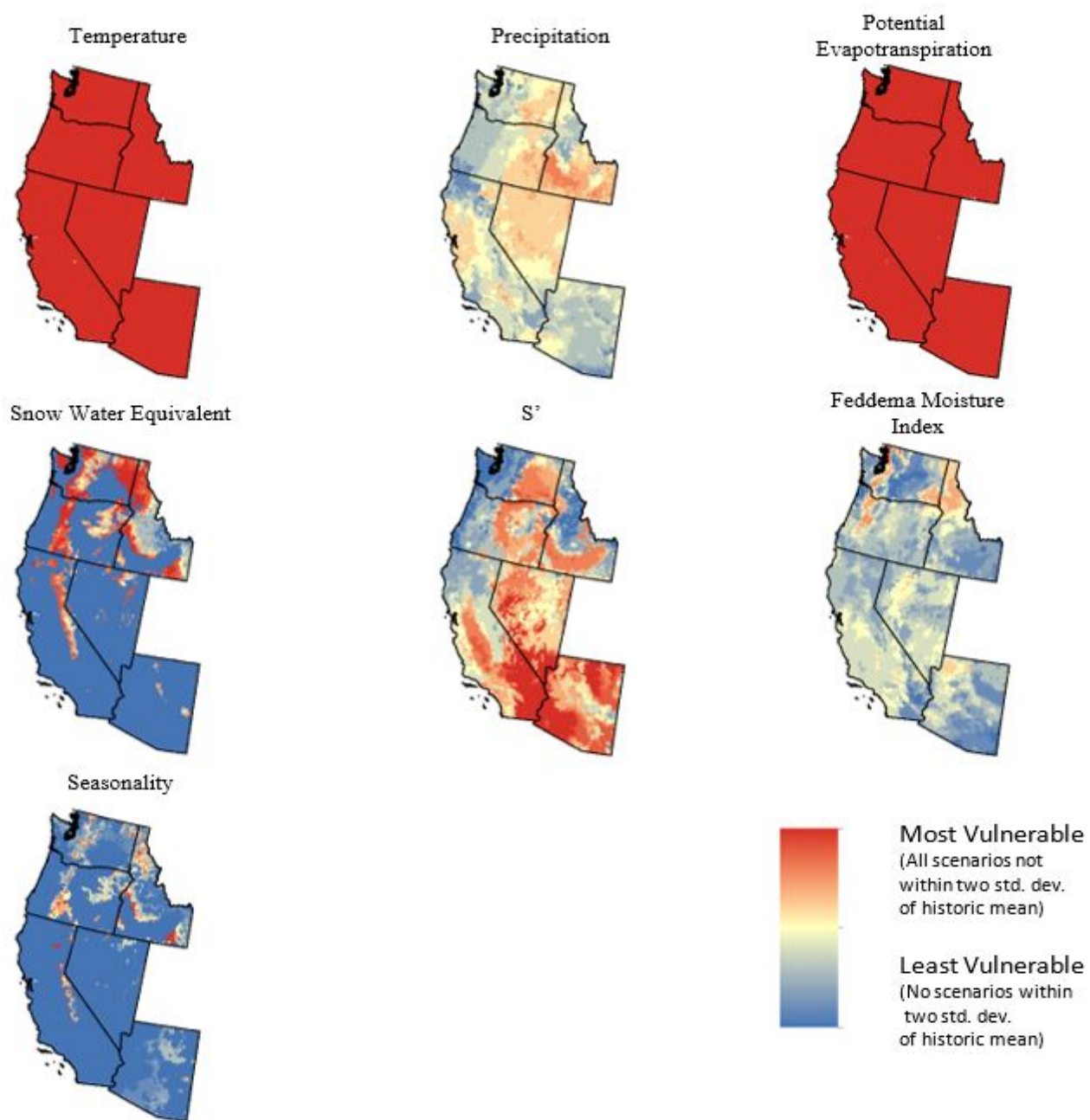


Figure 2. Vulnerability indices for temperature, precipitation, potential evapotranspiration, snow water equivalent (April 1), S' (available water), Feddema Moisture Index, and seasonality. The least vulnerable locations are those projected to be within two-standard deviations of the historic (1901-2010) mean in all nine climate models (Jones et al. in prep).

Conclusions

Subtask 1: The HL concept has proved useful for providing an understanding of hydrologic behavior at individual units and watershed scales across large geographic regions. Our work provides a planning approach that allows resource managers to consider historic and projected climate behavior in their long-term planning efforts, so they can better assess the risk imposed by potential changes. The methodology also allows stakeholders to focus on areas of interest, which provides the flexibility necessary for the information to be relevant across applications and sectors. The approach could be applied to the entire conterminous U.S. to provide resource managers with a better understanding of the projected vulnerability of water resources. However, subsurface permeability is currently not available nationally, so such an analysis would not be able to consider effects of this component.

Subtask 2: Isoscapes were highly useful in documenting how source waters change in major rivers seasonally and annually as well as identifying key water sources during critical periods of low flow but high demand. It is important to develop isoscapes for each basin of interest as the major drivers of isotopic variation are not consistent between basins. Information on the origin of water within major rivers can help managers identify potential causes of impairment and identify key parts of the basin providing water during critical low-flow periods. We are now working to link this information with processes such as thermal refugia (Faulkner et al. 2012).

Publications resulting from this research

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Task Title: CIVA-2.4 – Indicators of climate change in forested watersheds

Task Lead: E. Henry Lee

Task Description

This research focuses on the condition, or health, of forests and associated watersheds to better understand how changes in forest condition due to climate change via growth, pests, disease, fire or management will affect watersheds. Of concern is decreased forest productivity and increased tree mortality associated with climate-induced physiological stress and interactions with other climate-mediated processes such as pest and disease outbreaks leading to increased fire frequency. We conducted research to support the EPA Office of Water (OW) priorities to improve data and statistics for temperature, stream flow, and precipitation, and identify watersheds at risk from climate change. Further, the research supported the Office of Air and Radiation (OAR), Climate Change Division in the development of climate change indicators.

Background

The potential degradation and loss of forest cover from watersheds due to rising temperatures and decreasing snowpack is a major threat to water quality, particularly in the western United States. Forests cover about 47% of the land area in the Pacific Northwest (PNW)⁵ and provide much of the water for human use—forested watersheds are the source of over 80% of Oregon's water⁶. Healthy forests are critical for maintaining water quality by shading the soil surface, stabilizing the soil, and reducing nutrient loss and sediment transfer to streams, and represent a vital component of watersheds.

The PNW domain in Washington, Oregon and Northern California represents an economically and ecologically important area that has the greatest amount of carbon stored in forest biomass than any temperate, tropical, and boreal forest ecosystem on Earth⁷. The diverse climate and landscape of PNW provides for a range of ecosystems from dry, fire-prone forests east of the Cascade Mountains to temperate rainforests on the west side (Figure 1)

⁵ Smith, W.B., P.D. Miles, C.H. Perry, S.A. Pugh. 2009. Forest resources of the United States, 2007. General Technical Report WO-78, U.S. Department of Agriculture, Forest Service, Washington Office, Washington DC. 336 pp. http://www.fs.fed.us/nrs/pubs/gtr/gtr_wo78.pdf.

⁶ Brown, T.C., M.T. Hobbins, J.A. Ramirez. 2008. Spatial distribution of water supply in the conterminous United States. *Journal of the American Water Resources Association* 44:1474-1487.

⁷ Law, B.E., Waring, R.H., 2015. Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests. *For. Ecol. Manage.* 355, 4–14. <http://dx.doi.org/10.1016/j.foreco.2014.11.023>

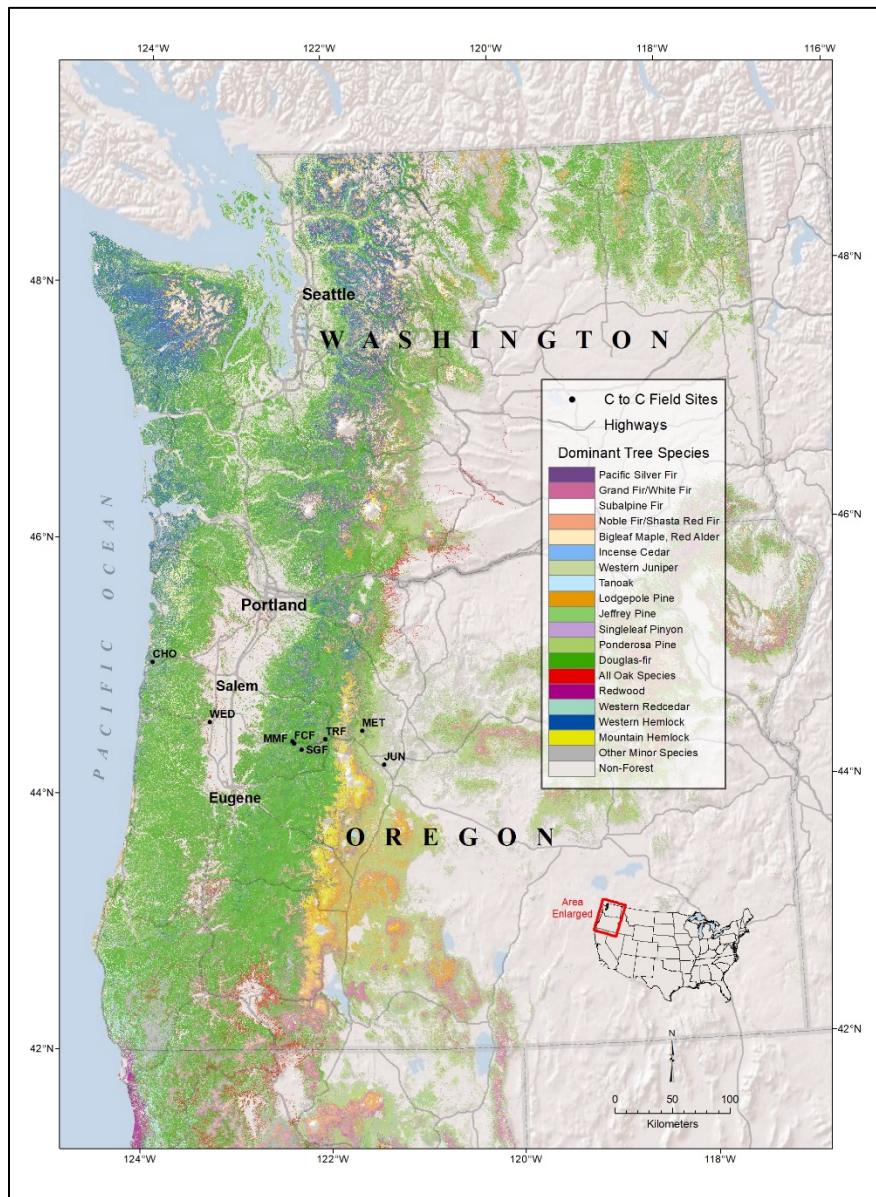


Figure 1. Spatial distribution of dominant tree species in the Pacific Northwest United States (U.S. Forest Service) showing the Coast to Crest (CtoC) monitoring network of permanent monitoring sites in western Oregon.

Recent evidence indicates that forests throughout the west are sensitive to temperature and drought stress, making them more vulnerable to disturbance⁸. Particularly concerning are potential increases in tree mortality associated with climate-mediated processes physiological

⁸ van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fule, M.E. Harmon, A.J. Larson, J.M. Smith, A.H. Taylor, T.T. Veblen. 2009. Widespread increase of tree mortality rates in the western United States. *Science* 323:521-524.

stress and interactions with other climate-mediated processes, which can jeopardize ecosystem services, including water quality and carbon sequestration.

With a predicted increase of pests, diseases, and fire frequency, understanding the interactions between climate and these disturbances is central to predicting climate change impacts to watershed structure and functioning at local and regional scales. Furthermore, understanding these interactions is critical for identifying and monitoring watersheds at risk from climate change, and for developing adaptation strategies to protect water resources.

Key information gaps and scientific uncertainties currently hinder our ability to predict tree growth and mortality in response to climate change and climate-mediated forest disturbances and require coordinated observation systems at regional and global scales⁹. Two key issues of concern in the PNW are the cumulative and interacting effects of fire, insects, and tree diseases and the impacts of climate change on snow accumulation and melt and their effects on regional hydrology¹⁰.

Approach

To monitor the effects of changing climate on PNW forests, the EPA in partnership with the U.S. Forest Service (USFS), has continuously measured tree growth along with meteorological and edaphic variables in forest stands from the Pacific Coast Range to dry eastern slopes of Oregon's Cascade Mountains (Figure 1) since the late 1990's. This Coast to Crest (CtoC) monitoring network includes three coast sites dominated by Douglas fir and western hemlock, Sitka spruce and western hemlock, and red alder in the Siuslaw National Forest; four on the west slope of the Cascade Mountains dominated by Douglas-fir and western hemlock in the Willamette National Forest; two sites, one dominated by Ponderosa pine and another dominated by western juniper, are located east of the Cascades in the Deschutes National Forest.

Meteorological stations at each location, forest floor, canopy top and an adjacent open area, continuously collect air temperature, relative humidity, temperature, and photosynthetically active solar radiation data (Figure 2). Also, soil moisture and temperature at 0.2 m increments to a depth of 0.6 m are automatically collected at each site.

⁹ Allen, C.D., A. Macalady, H. Chenchouni, B. Bachelet, N. McDowell, M. Vennetier, P. Gonzales, T. Hogg, A. Rigling, D.D. Breshears, R. Fensham, Z. Zhang, T. Kitzberger, J.-H. Lim, J. Castro, S.W. Running, G. Allard, A. Sermerci, N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259:660-684.

¹⁰ Dalton, M.M., P.W. Mote, A.K. Snover (Eds). 2013. *Climate change in the Northwest: Implications for our landscapes, waters, and communities*. Island Press, Washington, DC. 271p.



Figure 2. Meteorological stations: canopy top (center), forest floor (top left), open area (top right), soil temperature and moisture (bottom left).

Band dendrometers were installed on about 40 study trees at each site to measure seasonal tree growth (Figure 3). Ongoing research to understand the effects of biotic and abiotic stressors on forest condition includes the study of tree growth and mortality in response to temperature, drought, pests and diseases.



Figure 3. Band dendrometer on Douglas fir to measure seasonal growth. Inset: spring-loaded dendrometer with Vernier scale.

To supplement ongoing research at the CtoC sites, we developed a regional database of intra-annual tree-ring chronologies, stable isotope chronologies, and tree mortality rates of the economically and ecologically important tree species in the PNW (Figure 4). The dendrochronological and isotopic data are used to examine the interaction of climate and forest growth and disturbance that are key processes in forest ecosystem dynamics.



Figure 4. Tree mortality surveys conducted every 5-10 years track changes in forest health and condition (left). Tree core sampling to build a dendrochronological growth database for ecologically important tree species in the Pacific Northwest (right).

Over the past two decades, collaborative research with other federal agencies and universities has provided information on physical processes, forest succession, carbon sequestration, the rhizosphere, nutrient and water dynamics, tree growth, pests and diseases vis-à-vis changing climate and watershed health.

Findings

The climate of the PNW transitions from maritime to continental. Mild, wet winters and cool, dry summers are typical of coastal areas. The range of variation in mean monthly temperature tends to increase inland. Montane areas are subject to high winter snowfall. Annual precipitation is lowest in low, inland areas subject to rain shadow effects of mountain masses. Forests of the region are dominated by evergreen conifers. Douglas-fir dominates most of these mesic coniferous forest stands along with western hemlock and western redcedar. Subalpine forests are typically dominated by other coniferous species forming stands with somewhat lower basal area and biomass. More xeric forests, also having lower basal area, are typically dominated by Ponderosa pine east of the Cascades, while oaks become more prominent in the southern-most portion of the region. Climate change is not projected to cause major shifts in species dominance in PNW forests; however, some changes to total basal area and range shifts to higher elevation for some species is predicted across the PNW¹¹.

Extreme weather events including wind storms and flooding are common in the PNW. Flooding due to rapidly melting snowpack can cause substantial economic and ecological harm, particularly in combination with ensuing landslides. Research conducted on the CtoC sites shows that when warm, moist air masses along with relatively high winds—typical of winter storms—hit snow covered areas, 60±90% of the energy for snowmelt comes from sensible and latent heat exchanges rather than rain¹². Thus, heavy rainfall is not required for rapid loss of snowpack. Further, forested areas reduce the magnitude of the turbulent exchanges at the snow surface, so the contribution of rapid snowmelt to the runoff from forested areas is significantly less than non-forested areas during these events.

Spatial modeling of climate variables is critical for spatial assessments of watershed processes. CtoC research provided fine-scale observations to support the development, application, and assessment of methods to construct daily high-resolution meteorological grids at regional scales¹³. Solar energy influx is difficult to calculate for mountainous regions. CtoC observations provided sub-daily information show that including ground-level solar

¹¹Busing, R.T., A.M. Solomon, R.B. Mckane, C.A. Burdick. 2007. Forest dynamics in Oregon landscapes: Evaluation and application of an individual-based model. *Ecological Applications*, 17(7): 1967–1981.

¹²Marks, D., J. Kimball, D. Tingey, and T. Link. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a study of the 1996 Pacific Northwest flood. *Hydrological Processes* 12:1569-1587.

¹³ Daly, C., J.W. Smith, J.I. Smith, R.B. Mckane. 2007. High-Resolution Spatial Modeling of Daily Weather Elements for a Catchment in the Oregon Cascade Mountains, United States. *J. Applied Meteorology and Climatology* 46:1565-1586.

energy data significantly improves the performance of hydrologic models (Halama 2017, Halama et al. 2018).

Forests in the PNW sequester some of the largest amounts of carbon in the world and increasing atmospheric concentrations of CO₂ is hypothesized to increase sequestration via more efficient photosynthesis termed “carbon fertilization.” Our research has shown that sequestration of carbon in PNW forests is dependent on soil type and characteristics and is, therefore, unlikely to increase because of rising atmospheric CO₂¹⁴. Forests disturbed by logging or fire release excess carbon and nitrogen to streams in many regions of the U.S. Research including the CtoC sites shows that PNW forests growing on poor soils (low in nitrogen) and receiving low levels of anthropogenic nitrogen do not leak nitrogen compounds into streams¹⁵. The findings suggest that riparian dynamics, in-stream processing, and the presence of near-stream alders can affect concentrations of nutrients in streams more than the upland forest.

Forest growth in the PNW is affected by climatic, edaphic factors, pests and disease to varying degrees depending on topography and distance from the coast. Growth of Douglas-fir forests in the PNW is generally thought to be limited by soil moisture, but research at the CtoC sites showed that both temperature and soil moisture affect growth with temperature becoming more important at drier sites (Beedlow et al. 2013). Large conifer trees in the PNW use stored water to extend photosynthesis, both diurnally and seasonally. Studies on large Douglas-fir indicate that bole water content is an integral part of tree water dynamics enabling trees to extend carbon assimilation into drought periods and during periods when cold soil inhibits water uptake by roots, an adaptation that could benefit the survival of large PNW trees under climate change (Beedlow et al. 2017).

Patterns of tree growth and mortality in the PNW show evidence of climate-mediated changes and increasing disturbance from biological agents in Douglas-fir forests (Agne et al. 2017). With increasing winter temperature and more severe summer drought, growth rates are increasing at high elevation sites and decreasing at mid-elevation inland sites with little change in coastal areas since ~1990 (Lee et al. 2016, Figure 5). These patterns include recent declining trends in growth rates of several conifer species, increase in Swiss needle cast disease impacts on growth of Douglas-fir, increase in tree mortality due to suppression, shifts in phenology towards an earlier initiation of growth in cooler environments (Beedlow et al., 2017; Lee et al., 2013, 2016, 2017). In young coastal Douglas-fir, Swiss needle cast can reduce growth by half the potential rates through decreased supply of CO₂ for photosynthesis (Saffell

¹⁴ Beedlow, P. A., D.T. Tingey, D.L. Phillips, W.E. Hogsett, D.M. Olszyk. 2004. Rising atmospheric CO₂ and carbon sequestration in forests. *Frontiers in Ecology and the Environment*, 2(6), 315-322.

¹⁵ Cairns, M. A., K. Lajtha, P.A. Beedlow. 2009. Dissolved carbon and nitrogen losses from forests of the Oregon Cascades over a successional gradient. *Plant and soil*, 318(1-2), 185-196.

et al. 2014). Other pathogens such as dwarf mistletoe also significantly reduce growth in forests across the PNW. These mistletoe infections can take decades to kill trees, but preferentially infect faster growing trees within forests, shifting competitive status within forest stands (Marias et al. 2014).

Forest management has the potential to alter how forests respond to climate fluctuations. Within the PNW, management practices, such as thinning and fertilization, are common practices, but their impact on forest growth and resilience to drought depends on the local environment and spatial scale from trees to forests to landscape (Ruzicka et al. 2017). Forest thinning is commonly applied to decrease the effects of drought, but forest responses are quite variable and depend on what is limiting forest growth (Ruzicka et al. 2017). In the eastern Cascades, thinning of understory pines can stimulate growth even in Old Growth Ponderosa Pine through increased access to water (Sohn et al. 2014). The effects of a single thinning event are evident for decades both in increased growth and lower water stress (Sohn et al. 2014). But if water is not the limiting resource for growth, thinning can increase water use and water-use efficiency at the individual tree scale through increasing canopy exposure and increased leaf area (Ruzicka et al. 2017). Forest fertilization is the most common management practice across the PNW to increase forest yield (Cornejo-Oviedo et al. 2017). Forest productivity is tied to site fertility and quality, but fertilization does not always have the expected result. Isotopic analysis of tree rings at long term fertilizer trials have illustrated that fertilization increases growth first through increased leaf nitrogen levels which raise the photosynthetic rate of existing foliage (Cornejo-Oviedo et al. 2017). Increased growth from fertilization is sustained through production of greater leaf area. However, in sites where water is also limiting, this increase in leaf area can also increase forest transpiration increasing the risk of drought and drought impacts. Thus, forest managers need to consider the balance of water and nutrients on forest growth and health before prescribing forest management actions.

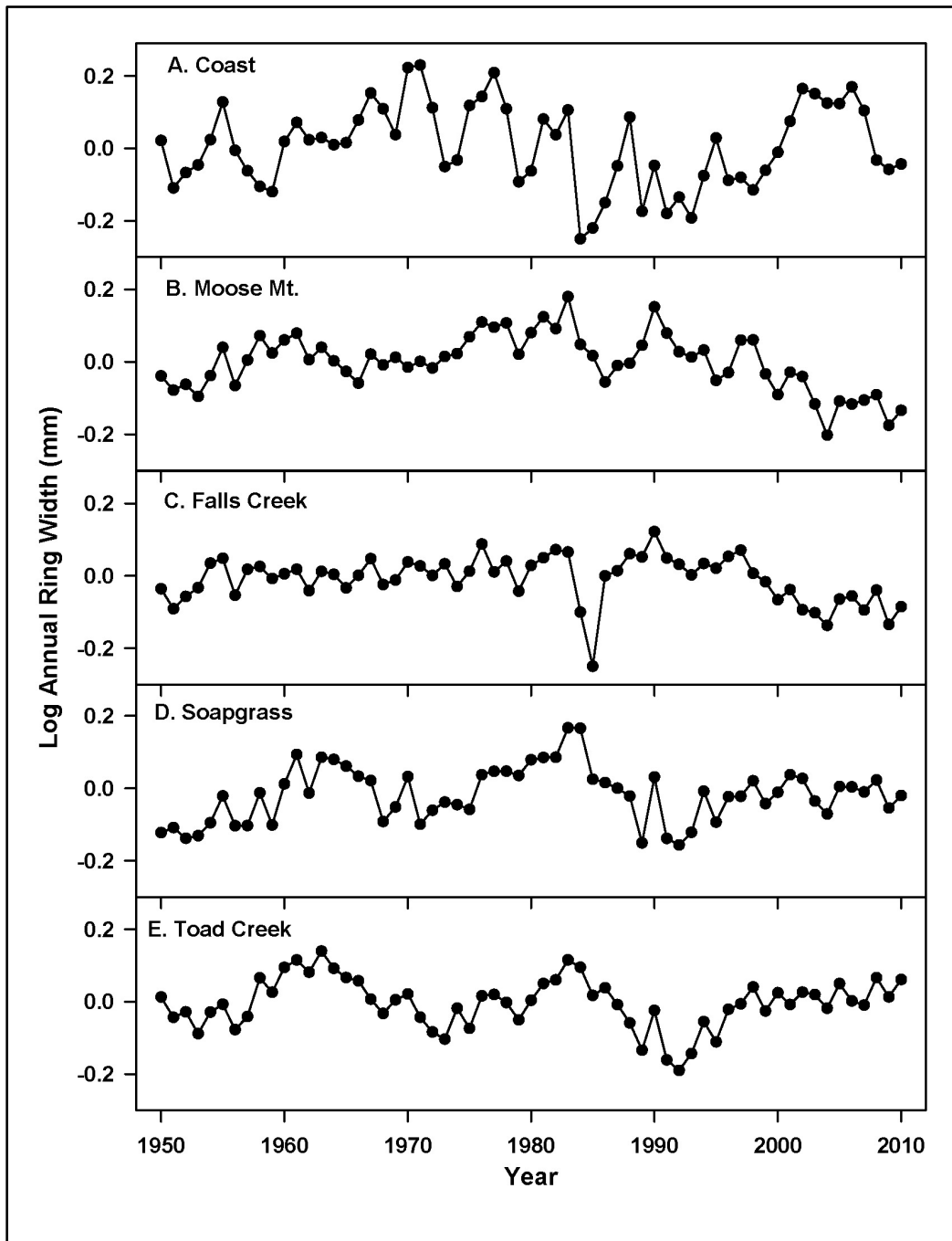


Figure 5. Tree-ring chronologies of mature Douglas-fir from CtoC monitoring sites. Tree growth at the Coast site (A) are affected by Swiss needle cast disease, which is influenced by climate. Declining growth rates of Douglas-fir at two mid-elevation sites (B & C) are associated with rising air temperature and increasing drought. Growth rates at high elevation (D, E) are increasing due to warmer winters and earlier snowmelt.

Conclusions

Episodic and chronic disturbances interacting with biological factors and climate substantially impact the structure and functioning of forested watersheds in the PNW. Warmer winters contribute to increasing severity of Swiss needle cast at higher elevations and latitudes within the Douglas-fir region (Lee et al., 2013, 2017). Bark beetles and root diseases could become more prevalent due to increasing summer drought, fire and increased tree water stress (Agne et al., 2017).

Effective, adaptive management actions in the face of changing climate must consider the abiotic and biotic factors influencing the responses of forested watersheds to disturbances such as wildfires and the consequential implications for water resources in the PNW. A better understanding of the interacting effects of climate change and changing pest and disease dynamics on forest health and watershed condition is required to develop a conceptual basis from which risks to water resources can be assessed.

Publications resulting from this research

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Task Title: CIVA-2.5– Synthesis and Assessment of Climate Change Effects on Water Quality and Aquatic Ecosystems

Task Lead: Thomas Johnson

Task Description

Climate change presents an increased risk of water quality impairment and inability to meet water quality management goals. Anticipating and planning for these impacts is critical to the long-term success of EPA’s national water program. This task developed a comprehensive summary and synthesis of currently available scientific literature detailing potential climate change effects on water quality (hereafter referred to as the *Water Quality and Climate Review*, or WQCR). The WQCR was developed as a web-based product to facilitate access to relevant information by diverse users with different information needs (e.g., users looking for information relevant to a particular EPA region or program). Beyond summarizing the literature, the assessment attempts to draw conclusions that extend our understanding beyond that provided by individual studies.

Background

Climate change in the U.S. is anticipated to include warming temperatures, with regionally variable changes in the amount and seasonal timing of precipitation. An increasing frequency of heavy precipitation events and longer dry periods between precipitation events is also likely. These changes will have direct and cascading effects on water quality. Effects will vary regionally and in different watershed settings but are not well understood. Until recently, relatively few studies have addressed climate change effects on water quality. There is now, however, an emerging literature in this area.

The goal of this Task was to provide EPA and EPA clients with concise, technical reviews of the scientific and technical literature addressing climate change effects on water quality. Literature reviews are intended to benchmark the current state-of-the-science concerning the effects of weather and climate on water quality, and to characterize the risk of future impacts to inform EPA water quality adaptation planning. The primary audience is EPA Office of Water (OW) and Regional staff. Other users include EPA clients such as State agencies, tribes, local/municipal governments, water utilities, and other stakeholders interested in water quality protection and management.

Approach

The WQCR was developed as a web-based product to facilitate easy access to information. It includes technical literature reviews addressing climate change effects on 8 water quality related topics (aquatic communities, cyanoHABs, nutrients, pathogens, salinity, sediment,

water temperature and streamflow); and summaries of hydrological and water quality changes most relevant to 8 EPA water programs (bioassessment, drinking water, estuaries, NPDES/wastewater, stormwater, TMDL/watershed protection, tribes/vulnerable populations and wetlands) (See figure 1). Technical information can be accessed by water quality topic (e.g., nutrients, pathogens), geographic region (e.g., northeast), or relevance to different EPA water programs (e.g., stormwater, NPDES) (See Figure 2). Users seeking to conduct their own assessments can also find guidance about assessment methods, modeling tools, datasets, and case studies from across the nation.

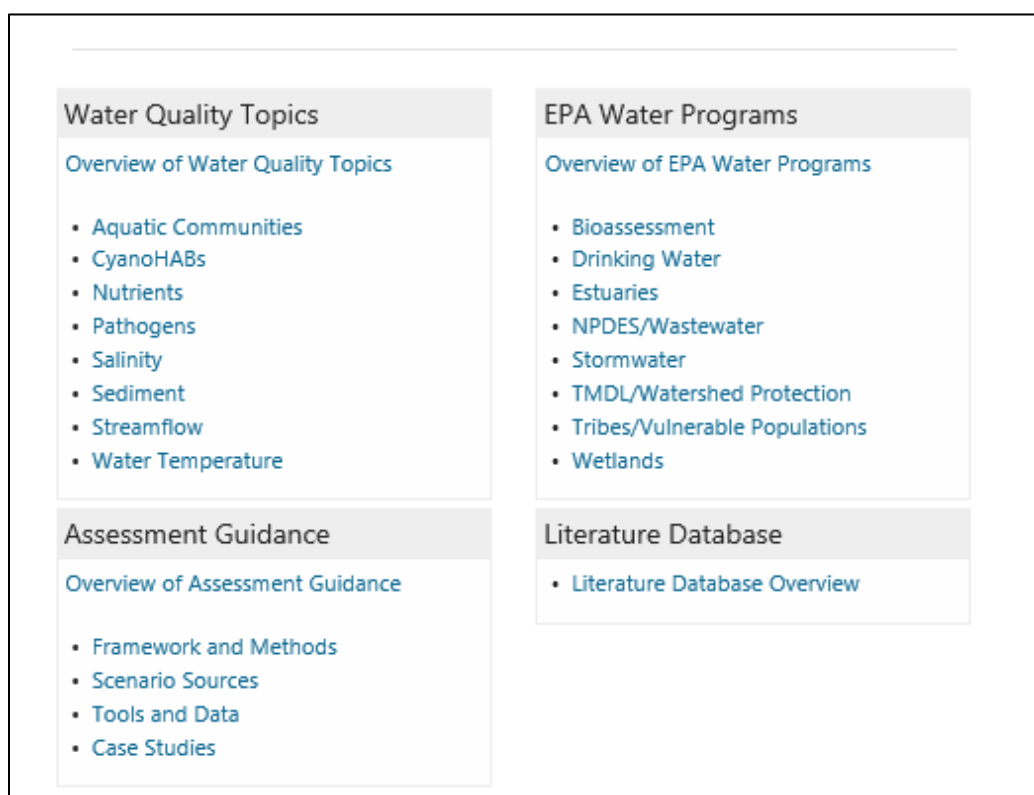


Figure 1. Key components of the Water Quality and Climate Review web site.

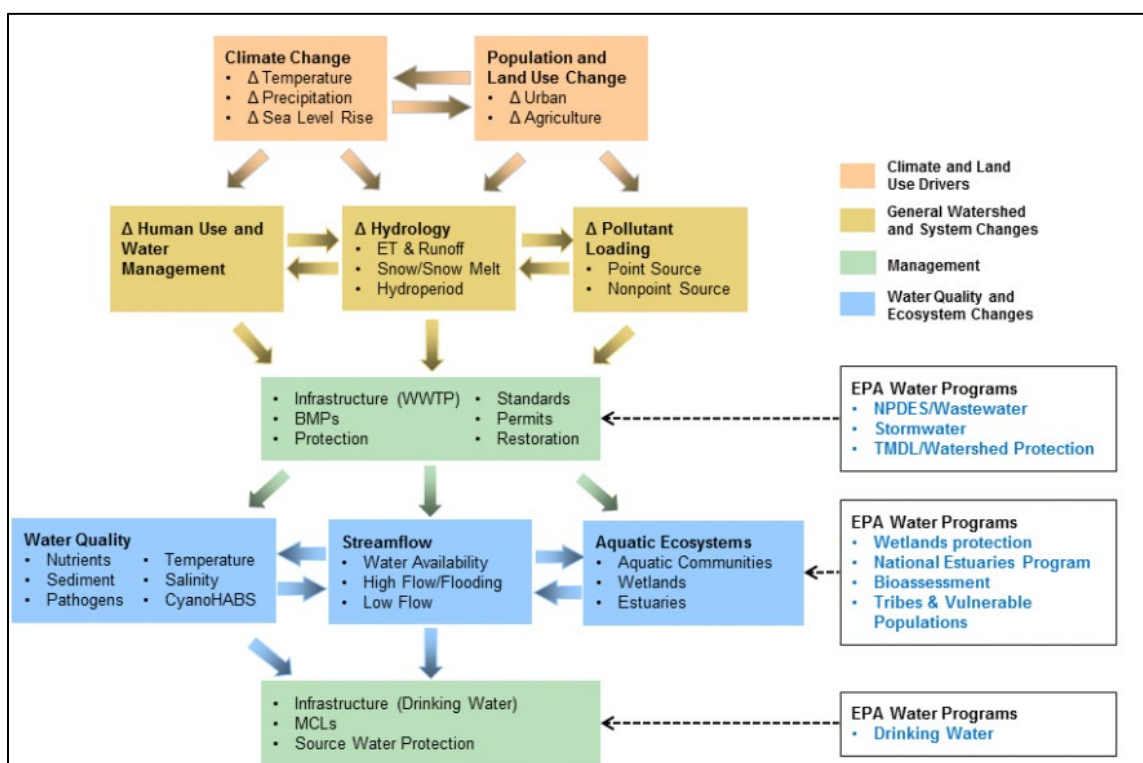


Figure 2. Potential climate change effects on water quality and relation to EPA water programs.

Findings

The effects of warming air temperatures and changes in precipitation on water quality vary regionally and in different watershed settings, and are strongly mediated by physical setting (e.g., geology, topography), land use, and human use and management of water (Paul et al., 2018; Coffey et al., 2018). Future changes are better understood for some attributes than others; water temperatures are expected to increase in much of the U.S., and sea level rise will exacerbate the risk of salt water intrusion, whereas changes in pollutant loads (nutrient, sediment, pathogens etc.) vary significantly and are generally correlated with changes in heavy precipitation events and streamflow. Increases in winter rainfall (all regions), reduced snowpack and earlier snowmelt (northern and mountainous watersheds) are suggested to increase winter-spring streamflow and contribute to lower summer-fall streamflow in some locations. Lower rates of streamflow in summer-fall could reduce assimilative capacity of waterbodies, potentially elevating pollutant concentrations downstream of point source discharges. Increases in water temperature are anticipated to be greatest in summer-fall when lower streamflow volumes reduce the thermal capacity of waterbodies. The risk of algal blooms in large rivers, lakes and estuaries could also increase due to an expanded seasonal window of warmer waters and the potential episodic increases in nutrient loading.

Conclusions

Climate change is anticipated to have direct and cascading effects on water quality, presenting a risk to human health and the environment. Responding to this challenge requires an improved understanding of potential changes, and the development of strategies for managing risk. The WQCR web site was developed to help EPA Program offices and Regions assess and plan for the potential effects of climate change on water quality. Detailed technical literature reviews benchmark the current state-of-the-science concerning how different attributes of water quality are sensitive climate. Results suggest all regions of the U.S. will be exposed to increasing risk of impacts, but impacts will vary in different regional and watershed locations. This information can help inform the development strategies for reducing risk in different regions of the U.S. Water planning requires local, site specific data, which is lacking for many locations. To address this, WQCR also provides links to data, tools, and case studies that support users interested in conducting their own vulnerability and risk management studies in specific locations.

Publications resulting from this research

The Water Quality and Climate Review web site (available on EPA's internal intranet):
<https://intranet.ord.epa.gov/ncea-wqcr/home>

Coffey, R., M.J. Paul, J. Stamp, A. Hamilton, and T. Johnson. 2018. A review of water quality responses to air temperature and precipitation changes 2: Nutrients, algal blooms, sediment, pathogens. *Journal of the American Water Resources Assoc* 55 (4): 844–868.
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Paul, M.J., R. Coffey, J. Stamp, and T. Johnson. 2018. A review of water quality responses to air temperature and precipitation changes 1: Flow, water temperature, saltwater intrusion. *Journal of the American Water Resources Assoc* 55 (4): 824–843
<https://doi.org/10.1111/1752-1688.12710>.

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Task Title: CIVA-2.6 – Regional Adaptation Case Studies for Sustainable Water Resources

Task Lead: Jeff Yang

Task Description

Hydroclimatic and water quality changes in local watershed can adversely impact the integrity and service functions of water infrastructure systems. In earlier research efforts, drinking water adaptation and engineering methods were investigated and results were published. Building on that research, this task was designed to produce actionable datasets, adaptation methods, and tools to support place-based adaptation of stormwater and wastewater infrastructure. The primary goal was to reduce climate projection uncertainties to help inform local adaptation actions. Specifically, wastewater and stormwater adaptation were investigated around the scientific and technological questions below:

- Within hydroclimatic provinces delineated in previous years, what precipitation changes require modification to the current engineering practice for stormwater and wastewater infrastructures? What change in precipitation intensity-depth-frequency (or design storm) may affect the stormwater management practice and the use of green/gray infrastructure?
- What changes in precipitation may adversely affect CSO occurrence and impact wastewater treatment plant performance in compliance with NPDES standards?
- Can adaptation in water and wastewater management systems be accomplished through the adaptive urban planning and engineering tool (AU-PET) that has been produced previously?
- For coastal areas specifically, what would be the risk of sea level rise and storm surge to wastewater and stormwater collection and transmission, and what would be adaptation solutions?

Background

Regional climate change studies including those by the Intergovernmental Panel on Climate Change (IPCC) and the United States Global Change Research Program (USGCRP) have shown a range of changes in future precipitation and hydrology across the U.S. Furthermore, significant coastal impacts are expected from storm surge and sea level rise. Superimposed on these climate change factors are dynamic population change and economic development at regional and local levels. These drivers challenge water professionals and EPA program managers who are tasked with sustainable infrastructure management in compliance with the CWA and SDWA regulations.

Distinct variation in hydroclimatic change is evident across the U.S. This requires region- and location-specific considerations for an effective adaptation. Before 2016, this research under ACE203 had examined the adaptation needs and options through case studies in three

selected hydroclimatic regions – Florida and the Southeast, Ohio River Valley, Las Vegas and the Southwest. A framework of long-term hydroclimatic modeling, short-term satellite-based forecasting, and integrated watershed modeling was established (EPA, 2018). In the 2016-2018 period, research and development were focused on adaptation tools for storm water, wastewater and drinking water infrastructure through regional case studies across the U.S. One emphasis was placed on coastal regions where interactions of climate systems take place, causing storm surge, high-intensity precipitation, urban flooding, and associated water quality changes. There is a broad need to quantify these impacts and develop adaptation measures for the built and natural environmental systems.

Approach

Through location-specific adaptation studies, this task produced actionable science for adaptation of water infrastructure in vulnerable coastal regions. The technical approach examined hydroclimatic projections, quantified changes in hydrological design basis through integrated watershed modeling, and hereby evaluated infrastructure adaptation options. The location-specific adaptation studies were conducted in collaboration with regions, states and local governments in order to evaluate the developed adaptation science and methods.

Figure 1 shows a fully developed procedure for local adaptation design in coastal regions. Through case studies, the methods were applied and tested in hydrological adaptation design to manage the risk in coastal stormwater and wastewater systems. Based on the case study

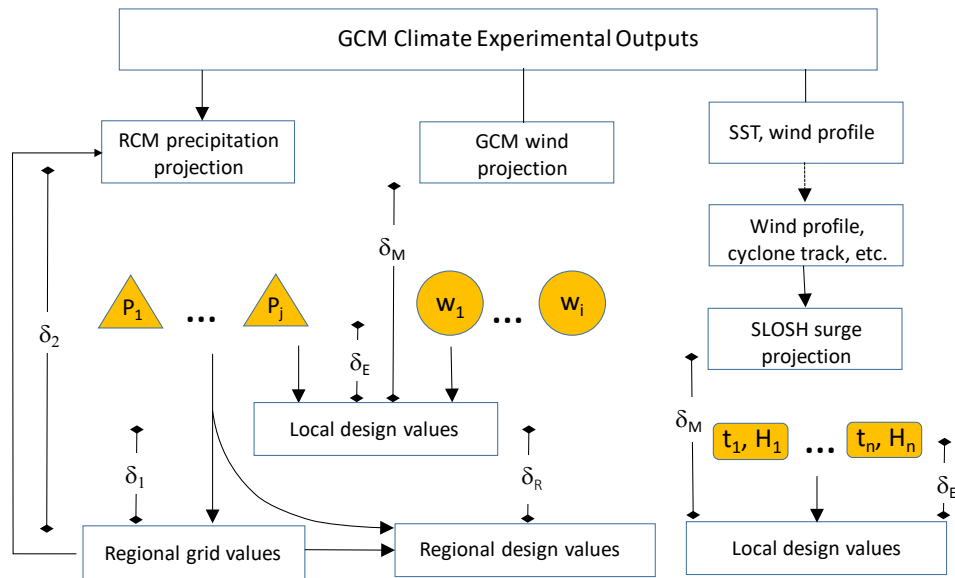


Figure 1. Developed procedure for quantitative analysis of design precipitation, wind, and storm surge inundation, and their uncertainties ($\delta_1, \delta_2, \delta_M, \delta_E, \delta_R$).

results, region-specific hydroclimatic vulnerability and commonalities of studied coastal areas are noteworthy. Overall, the case studies cover a diverse geographic area including:

- Mattapoisett and Lawrence in the Massachusetts east and southeast coast;
- Other locations along the U.S. Atlantic coast and the Gulf of Mexico: Bridgeport in Connecticut, Chesapeake Bay and Hampton Road in Virginia, Mobile and Mobile Bay in Alabama.
- Two case studies in the U.S. interior: Cincinnati, Ohio and Las Vegas, Nevada.

In all these case studies, advanced modeling and monitoring techniques were applied to assess the climate impacts. They include the storm surge simulation using NOAA's Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model, quantitative analysis of precipitation and flooding frequency by comparing Atlas-14, Bulletin-18 and newly developed statistical modeling techniques, and satellite imagery reconstruction of water quality in coastal bays and inland water reservoirs.

Findings

A lack of actionable science was identified as the major obstacle in climate adaptation (EPA, 2015). Subsequently this task project has developed a framework for water infrastructure adaptation, including methods and tools. The products include the engineering planning and design for water treatment plant adaptation (e.g., Li et al., 2014; Levine et al., 2016), the modeling methods to predicting hydroclimatic and land use changes on water quality (Ranatunga, 2014, 2017), and remote sensing of hydrological changes for adaptation design (Imen et al., 2016). These new developments are now integrated with the results from other CIVA projects to form the Smart Urban Designer (SUD) (EPA, 2018). The SUD framework in a three-level adaptation includes two products of this project: Water Treatment Plant – Climate Adaptation Model (WTP-cam) computer program (Li et al., 2014), and the transportation modeling methods/program in urban adaptation (Yao et al., 2014).

In coastal areas, a combination of sea level rise, precipitation variability and changes, and disruptive tropical cyclones can produce complex hydroclimatic impacts significant to water infrastructure and water quality programs. Major forms of impacts include surge-related inundation, increasing levels of precipitation and urban flooding, salt water intrusion, and short-term coastal water quality changes by hurricanes (e.g., Yang, 2016, 2018b). For example, SLOSH modeling at Mattapoisett (MA), Bridgeport (CT), Hampton Road (VA) and Mobile (AL) identified significant risk to water and wastewater treatment plants as well as water quality programs because of flooding and inundation under current and future sea level rise scenarios (Figure 2). Increased riverine flooding at Lawrence (MA) imposes higher risk to the City's drinking water plant than stipulated in the existing flood mitigation plans (Figure 3).

In all these case studies, actionable science was produced to support local communities for adaptation planning. In Mattapoisett (MA), the use of SLOSH, land use and evacuation traffic model simulation showed critical road congestions that could happen during hurricane emergence evacuation. These actionable results were reported through EPA regions to local governments (e.g., Yang, 2018a, b).

Finally, this task included a systematic analysis of the energy and urban efficiency in water infrastructure adaptation. In all case studies, it was found that the selection of specific adaptation options can significantly affect the energy consumption and efficiency of the infrastructure operations. These results are summarized in a series of publications (Yang, 2016, 2015; Yao et al., 2014; Tu et al., 2016; EPA, 2014, 2018).

Conclusions

The case studies have shown significant spatial and temporal variations of hydroclimatic impacts



Figure 2. SLOSH modeling results of storm surge inundation for category 4 hurricane and 4-ft sea level rise scenario, with impacts to the wastewater collection and transfer systems. Citizens were engaged in historical flood level identification as a part of the citizen science project.

Spicket River Flood Profile

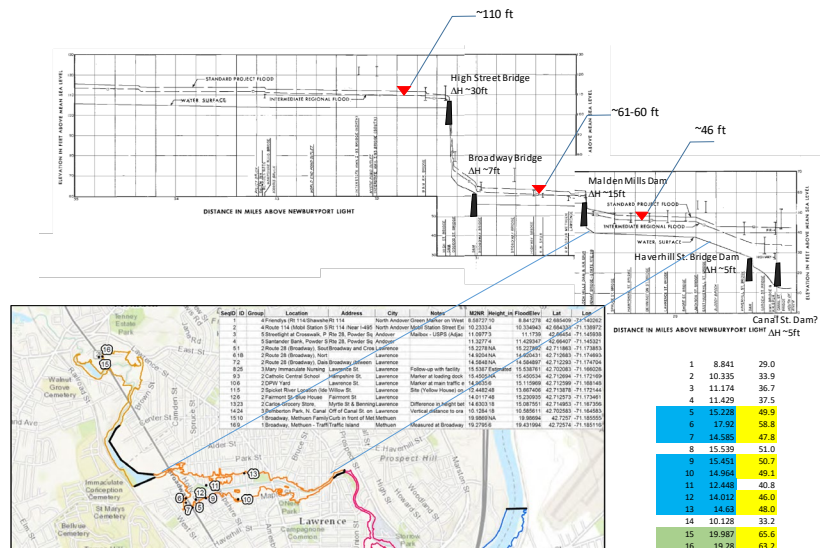


Figure 3. Reconstructed 2006 Mother day flood level in Spicket River in Lawrence, MA, showing the flooding levels exceeding 100-year flood plains, because of the increasing high-intense precipitations in recent decades. From Yang (2018a).

across the U.S. interior and coastal regions. These impacts differ in types and magnitude at a spatial scale much finer than those of climate model projections and regional design guidelines. Local factors and location-specific design basis should be considered to improve the resilience and service functions of water and other urban infrastructure. This is particularly important to coastal areas as demonstrated in five location-specific studies.

In adaptation planning, systems analysis is essential for characterizing hydroclimatic impacts and evaluating adaptation options. Long-term changes and short-duration disruptive events such as hurricanes and tropical storms can produce complex hydrological and water quality impacts at a given location. Dynamic population and land use changes can further exacerbate the complexity in hydrological and water quality response. In assisting practitioners and local governments, a systems analysis framework SUD and associated modeling tools are now available for evaluation of design basis and adaptation options.

Publications resulting from this research

- EPA (2018). National Water Infrastructure Adaptation Assessment, Part II: Smart Urban Designer (SUD) and Application Case Studies. *EPA 600-X-18-138*. 300p. In clearance. ([ORD-027981](#))
- EPA (2015). National Water Infrastructure Adaptation Assessment, Part I: Climate Change Adaptation Readiness Analysis. *EPA 600-R-15-138*. 124p. ([ORD-013038](#))
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- Levine, A.D., Yang, Y.J., and Goodrich, J.A., (2016). Enhancing climate adaptation capacity for drinking water treatment facilities. *J. Water and Climate Change*. DOI: 10.2166/wcc.2016.011. ([ORD-014392](#))
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- Ranatunga, T., Tong, S. T.Y., and Yang, Y. J., (2017). An approach to measure parameter sensitivity in watershed hydrological modelling. *Hydrological Sciences Journal*, 62, 76-92. ([ORD-005449](#))
- Ranatunga T., Tong S. T.Y., Sun Y., Yang J.Y., (2014). A comprehensive approach to total water management: A case study of the Las Vegas wash watershed, Nevada. *Physical Geography*, 35(3), 220-244. ([ORD-014392](#))
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- Yang, Y.J., (2015). Water-energy nexus studies and climate change adaptation assessment for urban infrastructures. *DOE/EPA/NFS Energy Positive Water Resource Recovery Workshop*, Arlington, VA. [\(ORD-012456\)](#)
- Yao, Z., Wei, H., Wang, X., Liu, H., and Yang, J.Y., (2014). Scenario-based carbon footprint inventory tool for urban sustainable development decision support: The Cincinnati case study. *TRB 93rd Annual Meeting*, Washington, DC. [\(ORD-007174\)](#)

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Task Title: CIVA-2.7 – Regional Coordination and Implementation of Climate Change Mitigation and Adaptation; Region 10 Pilot

Task Lead: Steve Klein

Task Description

In this task, the U.S. Environmental Protection Agency Region 10, Office of Research and Development and Office of Water conducted a Pilot Research Project to consider how projected climate change impacts could be incorporated into a Clean Water Act 303(d) Temperature Total Maximum Daily Load (TMDL) and influence restoration actions in the Nooksack River Basin Endangered Species Act Salmonid Recovery Plan. The Pilot Project used a temperature TMDL being developed for the South Fork Nooksack River (SFNR), in Washington, to inform the TMDL process about options for adapting to climate change. An overarching goal of the pilot was to ensure that relevant findings and methodologies related to climate change adaptation were available for preparation of the SFNR Temperature TMDL.

Background

Global climate change has the potential for significant impacts on the nation's freshwater ecosystems. Stream temperature is projected to increase in most rivers under climate change scenarios due in part to increases in air temperature, while changing precipitation and snowmelt patterns could influence water levels and water flow. Increases in stream temperature and changes in stream hydrology could have substantial negative effects on cold water fish species such as salmon.

To help better understand the potential impact of climate change on achieving water quality and salmon recovery goals, we conducted collaborative project in the SFNR. The project used the development of a temperature TMDL for the SFNR by the state of Washington as a pilot for integrating climate change into a watershed specific plan for improving water quality.



“The Nooksack Indian Tribe relies on salmon for subsistence, commercial, cultural, and ceremonial purposes” —Oliver Grah, Water Resources Program Manager, Nooksack Indian Tribe

Approach

This project considered how projected climate change impacts could be incorporated into a Clean Water Act (CWA) 303(d) Temperature Total Maximum Daily Load (TMDL) and influence restoration actions in the Nooksack River Basin (WRIA 1) Endangered Species Act (ESA) Salmonid Recovery Plan. A temperature TMDL developed for the SFNR was used as the pilot TMDL for climate change adaptation (Figure 1). An overarching goal was to ensure that relevant findings and methodologies related to climate change adaptation were available for development of the SFNR Temperature TMDL.

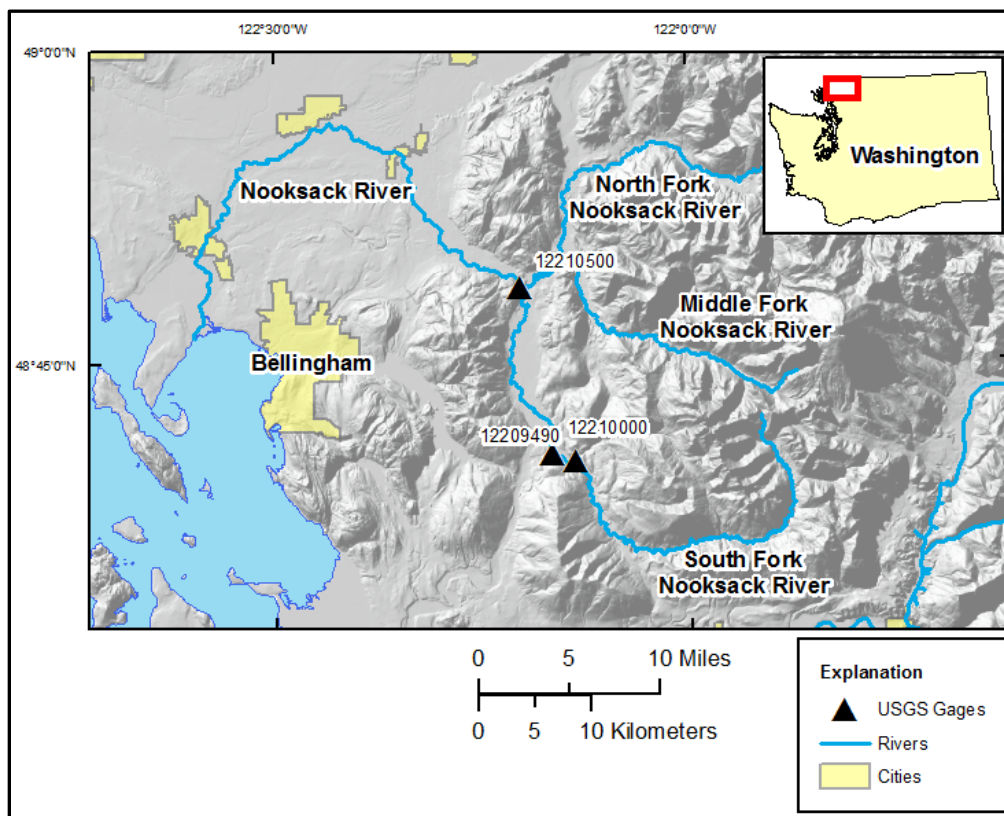


Figure 1. The Nooksack River, Washington, U.S.A.

This task was structured as a stakeholder-centric process, including active participation by the Nooksack Indian Tribe. The Research objective was separated into two assessments processes—one quantitative and one qualitative.

The quantitative assessment was directly responsive to the Clean Water Act (CWA) TMDL Numeric Cold-Water Temperature water quality standard (WQS). The quantitative assessment compared QUAL2Kw modeled stream temperatures, including riparian shading, with and without climate change for the 2020s, 2040s and 2080s. Further, modeled stream temperature was compared to the state’s Cold-Water Temperature Water Quality Standard (WQS) to inform the TMDL Implementation Plan. The analysis was embedded as a risk assessment to provide risk managers with an understanding of potential climate change impacts on stream temperature.

The qualitative assessment was a comprehensive analysis of climate change impacts on freshwater habitat and an evaluation of the effectiveness of restoration tools in the SFNR. The output of this assessment was a set of recommendations that informed development of the TMDL, updates to the WRAI 1 Salmonid Recovery Plan, and other land use and restoration planning efforts. Although quantitative methods were used in this assessment, there was no attempt to directly attribute the quantitative contribution of these stream restoration actions

on meeting the CWA TMDL Numeric Cold-Water Temperature WQS. The analysis comprehensively analyzed freshwater habitat for ESA salmon restoration in the SFNR under climate change and created a prioritized list of strategies that supports salmon restoration in SFNR under climate change.

Findings

The pilot research project results were published as Quantitative and Qualitative Assessments, which are available electronically on EPA's web site.

Quantitative Assessment

Results showed that the risk of higher water temperature will accelerate over time. Predicted increases in heat inputs and lower summer flows associated with a reduction in the storage of winter snowpack will combine to exacerbate summer water temperature extremes.

The model simulations suggested that, without restoration of riparian shade, water temperatures during critical summer low flow conditions could increase by amounts ranging from 3.5 to almost 6 °C by the 2080s. However, modeling also showed that restoration of riparian shading would significantly (30 to 60 percent) mitigate increasing water temperature.

Qualitative Assessment

Climate change impacts on temperature, hydrologic and sediment regimes could profoundly affect the distribution, life history periodicity, survival and productivity of salmonids in the SFNR. Results showed that the most important actions to mitigate the impacts of climate change in the SFNR are riparian restoration, floodplain reconnection, wetland restoration, and placement of log jams.

Conclusions

Climate impacts will extend throughout the year, from reduced discharge in spring to increased temperatures and reduced base flows in summer to increased peak flows in winter, rendering all salmon species and life stages vulnerable. The assessment results show that the most important actions to take in ameliorating the impacts of climate change in the South Fork watershed are riparian restoration, floodplain reconnection, wetland restoration, and placement of log jams.



Juvenile Chinook (*Oncorhynchus tshawytscha*)

Publications resulting from this research

Butcher, J. B., M. Faizullabhoy, H. Nicholas, P. Cada, AND J. T. Kennedy. 2016. Quantitative Assessment of Temperature Sensitivity of the South Fork Nooksack River under Future Climates using QUAL2Kw. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/233.
[\[https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NHEERL&dirEntryId=288533\]](https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NHEERL&dirEntryId=288533)

Qualitative Assessment: Evaluating the Impacts of Climate Change on Endangered Species Act Recovery Actions for the South Fork Nooksack River, WA. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/153, 2016.
[\[https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NHEERL&dirEntryId=320470\]](https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NHEERL&dirEntryId=320470)

Klein, S., H. Herron, J. Butcher. 2017. EPA Region 10 Climate Change and TMDL Pilot – South Fork Nooksack River, Washington Final Report. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-17/281.
[\[https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NHEERL&dirEntryId=338494\]](https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NHEERL&dirEntryId=338494)

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Task Title: CIVA-2.8 – Climate Refugia for Salmon and Other Cold-water Aquatic Taxa

Task Lead: Joe Ebersole

Task Description

This task examined cold water refugia for protecting the biotic integrity of watersheds under a changing climate. Climate refugia are areas that are buffered from climate change effects relative to other areas so as to favor greater persistence of valued social, physical, and ecological resources. This research used existing climatic and hydrological model results to overlay modeled stream temperatures, air temperatures, and other spatial data to predict locations and extent of potential climate refugia for sensitive cold-water taxa under current and future climates. Predictions were tested using monitoring data at multiple scales. Constraints were identified for refugia, and promising restoration and adaptation approaches were identified under current and future climates using a combination of empirical modeling, simulation modeling and targeted field-study approaches.

Background

Climate change is projected to substantially change air temperatures and precipitation patterns in the Pacific Northwest. Changes to stream and river ecosystems may include altered hydrologic and thermal regimes, introducing new or additional challenges to cold-water aquatic species such as salmon that are already stressed in many locations. Protecting such species is important both under the Endangered Species Act and to maintain the biological integrity of waters of the United States under the Clean Water Act.

The recognition and protection of climate refugia has been proposed as a potential adaptation strategy that may be useful for protecting the biotic integrity of watersheds under a changing climate. Climate refugia are areas that are buffered from climate change effects relative to other areas to favor greater persistence of valued social, physical, and ecological resources (Morelli et al. 2016). Paleo-ecological evidence suggests that refugia allowed species to persist through prior periods of climate change, even as surrounding regions became unsuitable. Now managers are asking how refugia might help species persist under future climates. The potential effectiveness of climate refugia as a climate adaptation strategy has several critical uncertainties, including: What physical processes create and maintain refugia? How are these projected to change given climate projections? At what spatial scales must these drivers be considered to maintain species within refugia? Given that paleo-refugia functioned in the absence of a significant human footprint, how will climate change and other anthropogenic stressors interact to constrain refugia effectiveness in the future?

In addition to these key uncertainties, other questions remain as to how the concept of climate refugia might be effectively implemented: Are current data (including national aquatic

assessments) sufficient to help inform the identification of potential refugia? What are implications for developing water quality criteria and standards?

Approach

To assist federal, state, and local officials in assessing the potential role of climate refugia to cold water species like salmon, ORD is collaborating with EPA Region 10, the States of Oregon and Washington, NOAA, and the U.S. Forest Service to identify potential refugia and assess their function and value to endpoints including water quality and endangered fish populations. Using mapping and modeling tools, ORD is providing an assessment of cold-water refuge frequency and quality in the Columbia River, and projected benefits to migratory salmon and steelhead. These tools are being used to examine potential benefits under future scenarios of water availability, management decisions, and other changes in environmental conditions.

Findings

Current refugia

Rivers fed by glaciers, annual snowpack, and groundwater currently contribute to cold-water refugia that provide critical habitats to migrating salmon and steelhead, many populations of which are listed under the US Endangered Species Act (Figure 1). Our published work illustrates processes regulating water temperatures at multiple scales ranging from localized influences of groundwater in intermittent streams (Ebersole et al. 2015; Figure 2), extensive floodplain hyporheic exchange and flowpaths (Faulkner et al. Submitted), to extensive longitudinal heterogeneity (Fullerton et al. 2015; Figure 3) driven in part by regional variation in snowpack and effects on streamflow and temperature (Leibowitz et al. 2015). The spatial arrangement of temperature, including reaches serving as seasonal refugia, within stream and river networks is expected to change with warming (Fullerton et al. 2017b) and will be an important factor in how fish populations are likely to respond to environmental change (Fullerton et al. 2017a).

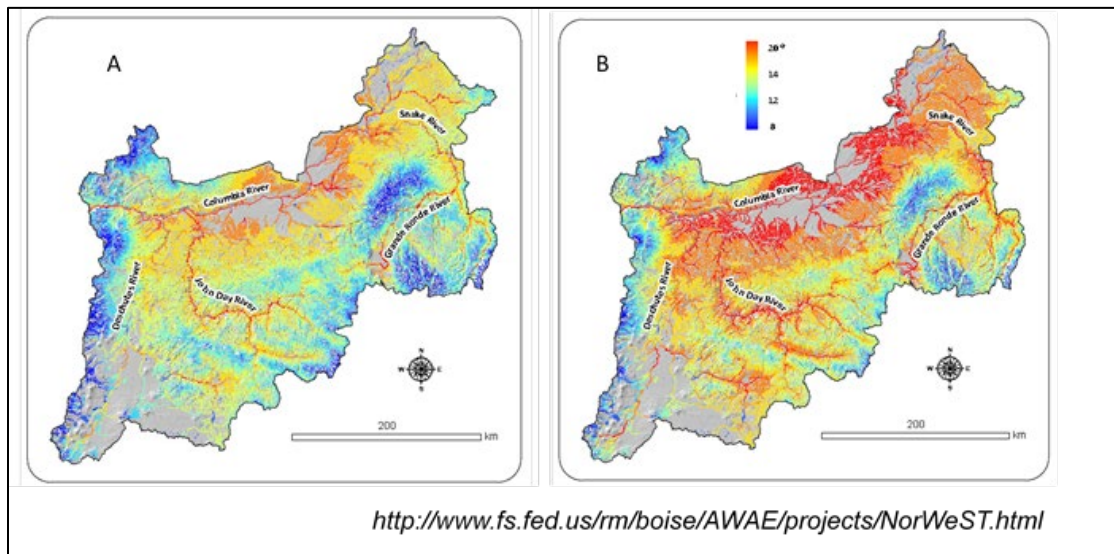


Figure 1. Predicted mean August water temperatures for the John Day River basin under recent (A) and 2080 (B) climate scenarios. Newly available crowd-sourced data and spatially-extensive modeling tools are allowing clearer pictures of water temperature patterns and likely future scenarios. Model output and figures provided by Dan Isaak, USFS, collaborator on a companion RARE grant to this Task



Figure 2. Cold-water refuges can occur at tributary junctions where colder streams flow into warmer rivers. This is a well-known phenomenon. Our work (Ebersole et al. 2015) demonstrated that even after tributaries cease to flow on the surface, and appear dry, they can continue to contribute cold, sub-surface water to create cold-water refuges at tributary junctions. This highlights an important hydrologic connection between intermittent and ephemeral streams that appear to be dry on the surface, but which may in fact be contributing important resources, such as cold hyporheic flows, to downstream waters.

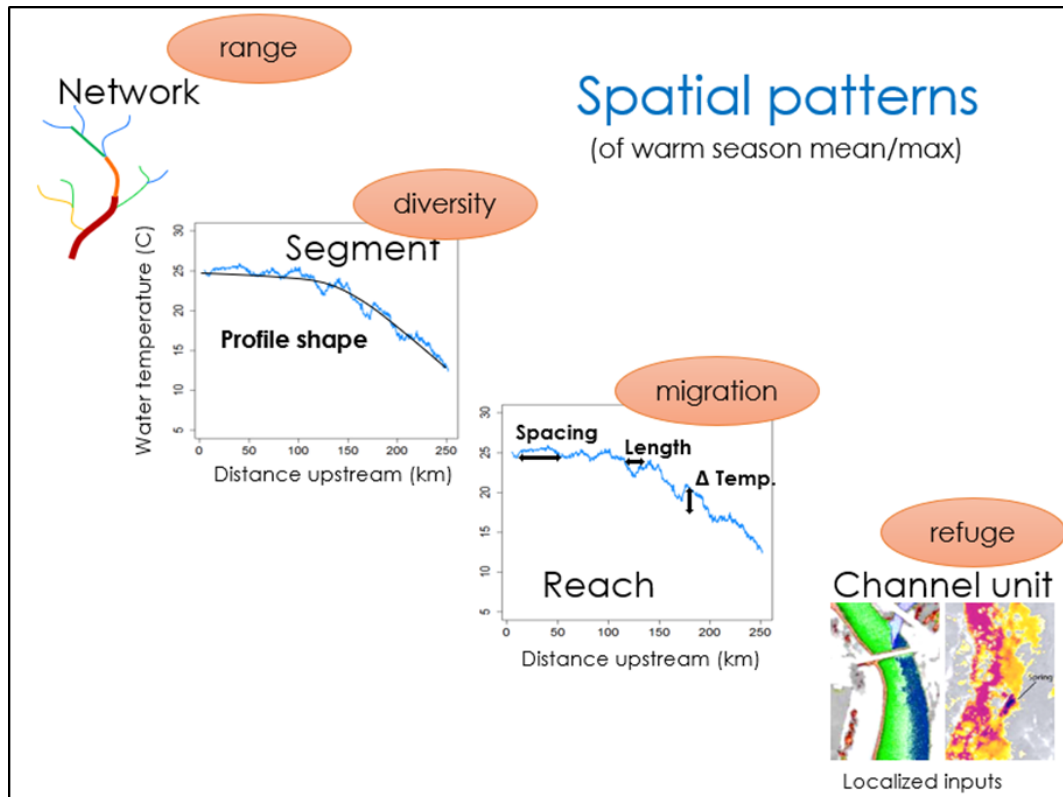


Figure 3. Spatial variation in water temperature, and the distribution of associated cold-water refuge habitats, occurs at a range of scales. Figure courtesy Aimee Fullerton, NOAA. See also Fullerton et al. 2015.

Assessing refuge effectiveness and ‘sufficiency’

Of particular interest to EPA Region 10 and the States of Oregon, Washington and Idaho is the status of water temperature and limitations on migrating adult salmon and steelhead (<https://www.epa.gov/columbiariver/columbia-river-cold-water-refuges>). Cold-water areas in the Columbia River currently support temperature refuges for over half of the steelhead and a quarter of the fall Chinook salmon in the Columbia River during thermally-stressful periods (Figure 4). These features are predominantly located in the Columbia Gorge, and fed by high-elevation sources that are experiencing declines in snowpack and snowmelt predictability. State and federal regulatory agencies are asking whether existing and potential future availability of cold-water is sufficient to support populations of salmon and steelhead into the future. To address this need, we developed a simulation modeling approach that allows quantification of energetic costs and benefits to salmon and steelhead as they migrate through a thermally-diverse riverscape (Snyder et al. 2019). In concert with EPA Region 10, the States of Oregon and Washington, and NOAA, we developed maps of cold-water refuges

in the Columbia River and are running simulations of migration pathways through this corridor (Figure 5).

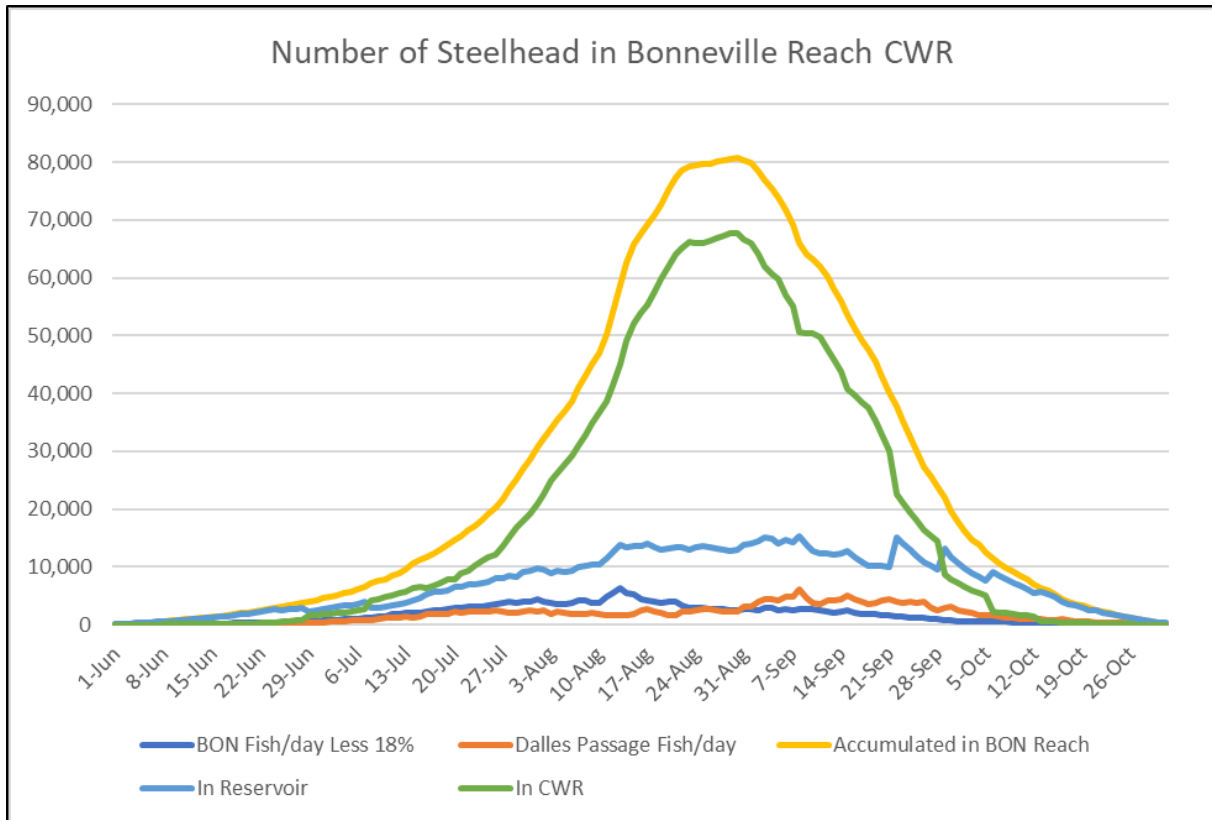


Figure 4. Number of adult steelhead using cold water refuges (CWR, green line) in relation to those using other parts of the Bonneville Pool portion of the Columbia River and passing Bonneville (BON; dark blue) and The Dalles (red) Dams.

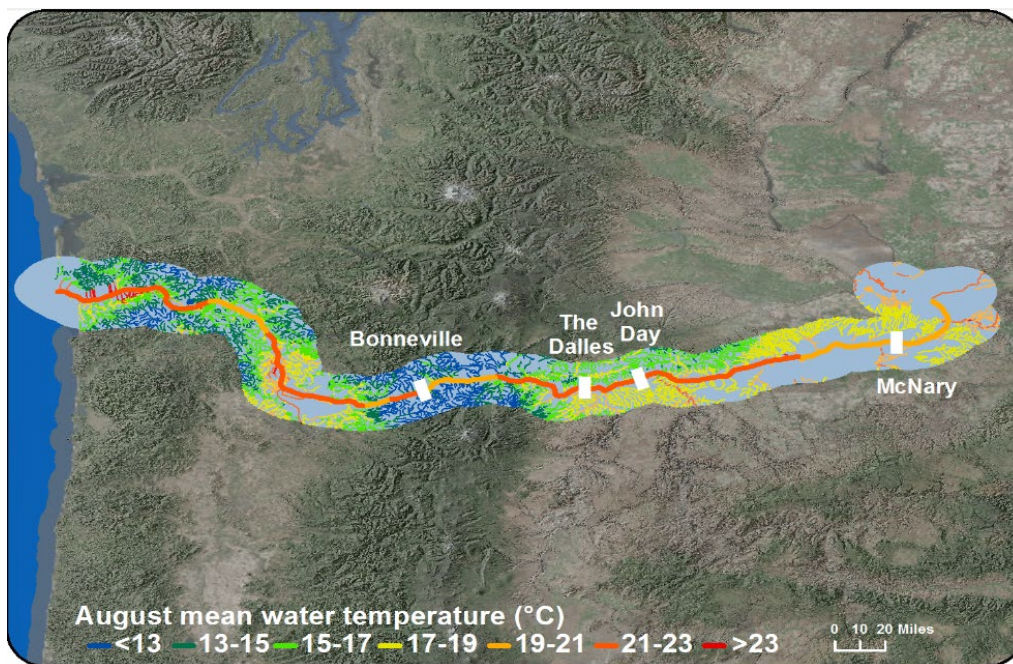


Figure 5. Map of the Columbia River (thick line) along the border of Oregon and Washington, showing the locations of four dams (white bars) and tributaries color-coded by mean August water temperature. Blue tributaries (colder than 15°C) are among those important as cold-water refugia for adult salmon and steelhead migrating through the Columbia River (red and orange, representing temperatures exceeding 19°C).

Managing climate refugia for cold-water fishes

Once cold-water refuges are identified, the challenging work of assessing management needs for the protection and restoration of these resources begins. We provided guidance for climate refugia management in Morelli et al. (2016; Figure 6) building from the climate conservation cycle developed by West and Julius (2014; see also CIVA 2.9, this report). The most recent product from our work is a paper submitted to a special issue of *Frontiers in Ecology and the Environment* focused on climate refugia (Ebersole et al. Submitted). The provides a review of the state of the science for climate refugia for cold-water fish, with an emphasis on adaptation management strategies. Examples of creative approaches being implemented in the US Northeast and Pacific Northwest are highlighted. The topic encompasses issues of anticipated climate change impacts to water quality and sensitive fish populations and includes potential interactions with water use and habitat modification. Management for climate refugia may have implications for EPA water quality standards and state/tribal guidance, and interagency consultations on water quality and habitat issues, so this issue will be of particular interest to the Office of Water, and to Regions 10 and 1 because of its emphasis on coldwater fish species and inclusion of case studies from those regions.

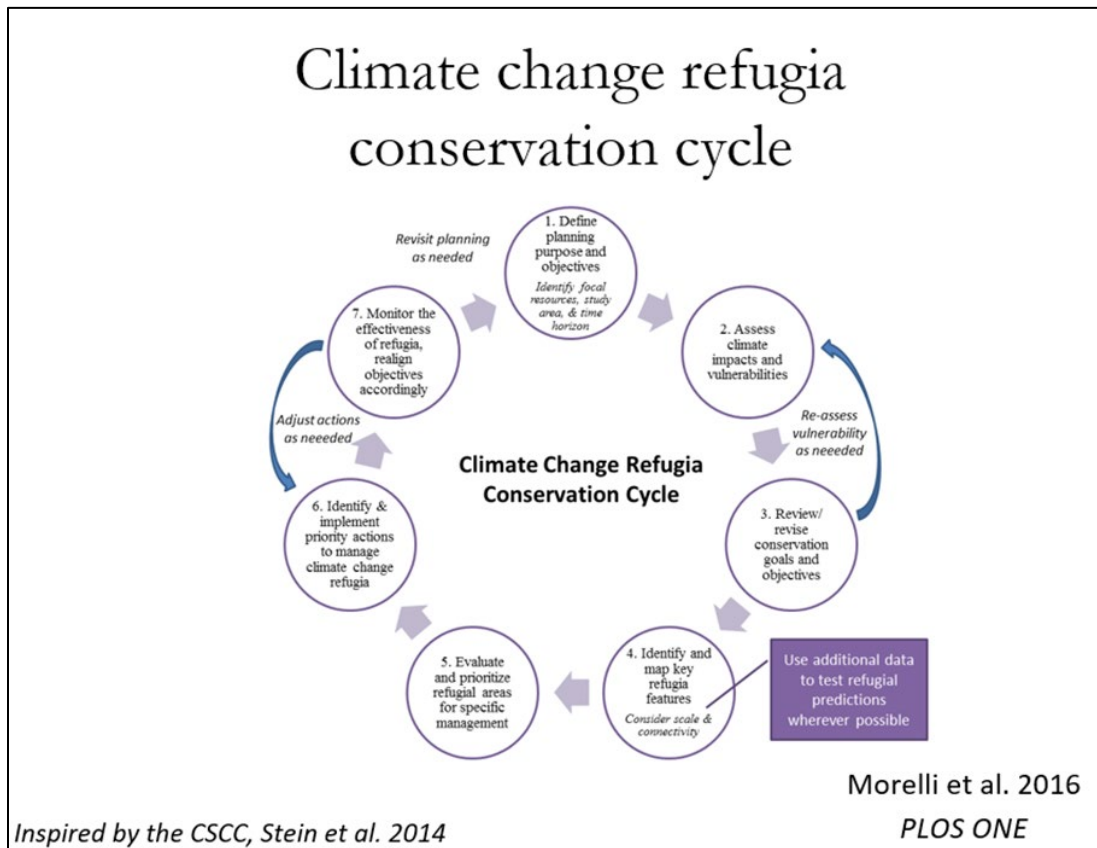


Figure 6. The climate change refugia conservation cycle (Morelli et al. 2016).

Conclusions

Cold-water refugia are allowing salmon and steelhead populations to persist despite increased warming of rivers. Future maintenance of existing refuges will be dependent upon snowpack and groundwater availability as influenced by environmental change and patterns of human use. Restoration potential and enhancement of existing refuges will be dependent upon water quality, and water availability and timing. Tools developed as a part of this research are being used by EPA Region 10 and NOAA to evaluate the role of cold-water refuges.

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- Ebersole, J. L., R. Quinones, S. Clements, and B. Letcher. Submitted. Climate refugia for cold-water fishes under an expanding human footprint. *Frontiers in Ecology and the Environment*.
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- West, J.M., S.H. Julius, 2014. Chapter 8: The Art of the Possible: Identifying Adaptation Options. *In*, Stein, B.A., P. Glick, N. Edelson, and A. Staudt (eds.). *Climate-Smart Conservation: Putting Adaptation Principles into Practice*. National Wildlife Federation, Washington, D.C., pp. 119-140. (CIVA 2.9)

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Task Title: CIVA-2.9 – Climate Change Adaptation Framework for Ecosystem Management

Task Lead: Jordan West

Task Description

This task focused on adaptation planning frameworks, methods, and tools (with a case study concentration on coral reef management), in support of EPA's mission and responsibilities as defined by the Clean Water Act (CWA). Specifically, it was directly responsive to research needs under OW priority #8 (Indicators of climate change), as well as needs of EPA Regions with coral reef jurisdictions. The work is designed to build the capacity of EPA OW, regional offices, inter-agency partners, aquatic ecosystem managers, and other decision-makers to assess and respond to global change impacts on ecosystem processes and services. As such, the work included components on how to compile, transform, and convey information from vulnerability assessments and resilience assessments and feed it into structured decision-making processes for adaptation planning.

Background

The interactive and cumulative impacts of climate change on natural resources such as coral reefs present numerous challenges for conservation planning and management. Climate change adaptation is complex due to climate-stressor interactions across multiple spatial and temporal scales. This leaves decision makers worldwide faced with local, regional and global-scale threats to ecosystem processes and services, occurring over time frames that require both near-term and long-term planning. Thus, there is a need for structured approaches to adaptation planning that integrate existing methods for vulnerability assessment with design and evaluation of effective adaptation responses.

The purpose of this project was to synthesize general principles of adaptation to climate change at the national scale and across ecosystem types into an adaptation planning framework to support climate-smart natural resource management. Case study applications of the framework, carried out with partners on the ground, were used to demonstrate utility for vulnerable coral reef ecosystems. During this process, practitioner-partners communicated a need for an Adaptation Design Tool that would provide a more detailed, structured approach to break down the complex adaptation process into tractable steps. This tool was developed by EPA in collaboration with members of the interagency U.S. Coral Reef Task Force (USCRTF). Once the beta version of the tool was available, it was also adopted by the Chesapeake Bay Program for use in workshops on climate-smart design and strategic planning for black duck wetlands, seagrass and toxic contaminant management.

Approach

EPA participated in a climate-smart work group convened by the National Wildlife Federation to develop a unified adaptation framework designed to be tractable and accessible for use by all ecosystem managers nationally. The work group included over a dozen adaptation specialists from Federal and State governments, non-governmental organizations and

academia, who together examined the implications of climate change at every step of the management planning cycle (Figure 1). EPA's contribution to the resulting *Climate-Smart Conservation* guide included a chapter on principles for identifying adaptation options and applying climate-smart design considerations to management practices (West and Julius 2014). These principles, integrated into a modified version of the climate-smart cycle (Figure 1), were then used along with a literature review and expert elicitation workshop to establish a proof-of-concept for applicability of the adaptation design approach for coral reefs as a case study system. When coral reef practitioner-partners expressed a desire for an Adaptation Design Tool (Figure 2), the USCRTF afforded a platform and extensive network of experts from coral reef states and territories as well as EPA Regions who collaborated in the review, co-production and testing of the tool. The Nature Conservancy (TNC) then joined with EPA to convert the tool into an interactive online course that is permanently available on TNC's Reef Resilience Network. At the same time, EPA provided guidance and participated in workshops of the Chesapeake Bay Program in which the tool was applied to wetlands, seagrass and toxic contaminant management planning.

Findings

The case study application of the climate-smart adaptation framework tested the practical utility of the concepts using a place-based coral reef case study and workshop (West et al. 2016). This effort successfully translated high-level theoretical principles for adaptation into practical application methods for a specific ecosystem. We provided a proof-of-concept for coral reefs, presented a literature-based compendium of information for direct use by coral reef practitioners in brainstorming 'climate-smart' management actions, and vetted both the framework and the information compendium at a stakeholder workshop for testing and feedback. Lessons-learned from the workshop—which used a practical example of real-world adaptation planning processes in Hawai'i—resulted in stakeholder expressions of overall support for the approach and an interest in further development of tools for using the techniques to advance practical outcomes in the field.



Figure 1. Principles developed by EPA in the multi-disciplinary *Climate-Smart Conservation* guide (top) (West and Julius 2014) were tailored for use in case studies on adaptation planning for coral reef ecosystems (bottom) (West et al. 2016).

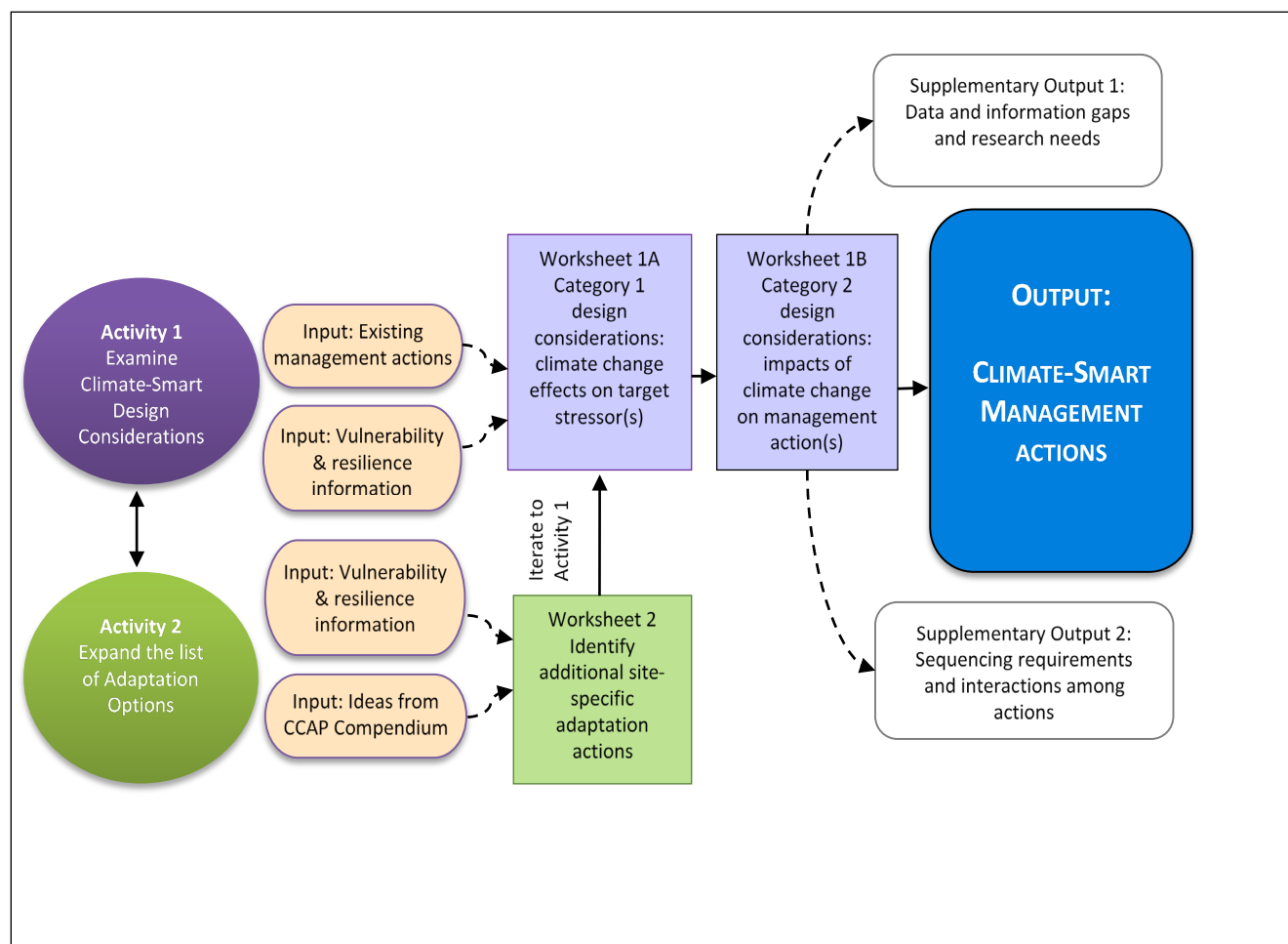


Figure 2. Adaptation Design Tool flow chart of activities, resources, and worksheets (Parker et al. 2017; West et al. 2018).

The subsequently developed Adaptation Design Tool (Parker et al. 2017, West et al. 2018) contains worksheets that guide users through a series of design considerations for adapting their planned management actions to be more climate-smart given changing environmental stressors; it also provides a method for brainstorming new adaptation options in response to climate threats not yet addressed in the current plan (Figure 2). Developed and tested in collaboration with practitioners in Hawai'i and Puerto Rico, the tool and associated reference materials consist of worksheets, instructions and lessons-learned from specific place-based examples. As of September 2018, the online, interactive training course for the tool (TNC 2017) had been viewed by over 300 participants from 60 countries and territories. At the same time, the U.S. Coast Guard requested an article on how the tool could apply to coastal issues of concern to Coast Guard operations (Gibbs et al. 2018). Meanwhile, the Chesapeake Bay Program also applied the tool in multiple "goal implementation team" workshops and modified it to also shed light on higher-level strategic planning (CBP 2018).

Conclusions

The West et al. (2016) compendium of information on adaptation options—with associated climate-smart design considerations—has established a thought process that explicitly links climate change impacts to management responses. This creates a bridge for managers to move from a "business as usual" or "more is better" design of management actions, to revision of actions so that the designs accommodate a range of plausible future conditions of the reef driven by climate change. The overall goal is to be able to develop and carry forward more robust climate-smart candidate actions as part of more rigorous evaluation and selection of priority actions for implementation.

The Adaptation Design Tool (West et al. 2018) assists this goal further by breaking down an otherwise overwhelming thought process into smaller steps. The process structured by the tool was well-received by participants of expert consultations in both the Pacific and Caribbean, with recognition that the process of using the tool is equally as valuable as the final design outputs. This is because the stepwise exercise identifies information gaps while creating a transparent record of currently-available information and judgements; it also elicits careful consideration of levels of uncertainty in different types of information, and whether mismatches between the scale of climate impacts and the scale of management actions may play a role.

While initially tested for coral reefs, the tool is also fully transferable to other natural resource systems and sectors, as demonstrated by the successful CBP (2018) effort to apply the tool not only for design of management actions, but also to inform higher level strategies. The adaptation framework and associated Adaptation Design Tool have advanced the practice of assessment and decision-making science, are informing higher level strategic planning, and are serving as a basis for systematic, transparent and inclusive thought processes to tackle the practical implications of climate change for ecosystem-based management.

Publications resulting from this research

Chesapeake Bay Program. 2018. Climate-Smart Framework and Decision Support Tool.

Chesapeake Bay Trust, Annapolis, MD.

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West, J.M., C.A. Courtney, A.T. Hamilton, B.A. Parker, S.H. Julius, J. Hoffman, K.H. Koltes, P. MacGowan. 2016. Climate-smart design for ecosystem management: A test application for coral reefs. Environmental Management. DOI: 10.1007/s00267-016-0774-3

West, J.M., S.H. Julius, 2014. Chapter 8: The Art of the Possible: Identifying Adaptation Options. *In*, Stein, B.A., P. Glick, N. Edelson, and A. Staudt (eds.). Climate-Smart Conservation: Putting Adaptation Principles into Practice. National Wildlife Federation, Washington, D.C., pp. 119-140. West, J.M., Courtney, C.A., Hamilton, A.T., Parker, B.A., Julius, S.H., Hoffman, J., Koltes, K.H. and MacGowan, P. 2016. Climate-smart design for ecosystem management: A test application for coral reefs. Environmental Management. DOI: 10.1007/s00267-016-0774-3

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Task Title: CIVA 2-10 – Watershed modeling to assess the effectiveness of management practices for adapting to climate change

Task Lead: Thomas Johnson

Task Description

The long-term success of water quality protection requires management strategies that are resilient to anticipated future changes in weather and climate. This task provides an improved understanding of how anticipated climate change impacts on water quality can be managed using currently available BMPs in different regional and watershed settings. Information about the feasibility of managing anticipated impacts contributes to understanding the vulnerability of watersheds and near-shore environments to climate change. Information about BMP placement and performance informs the development of management responses to climate change. The results advance the capacity of EPA and clients to assess and respond to potential climate change impacts on EPA's National Water Program.

Background

Anticipated future changes in air temperature and precipitation are likely to alter streamflow and water quality throughout the U.S. Impacts will vary according to specific regional changes in climate, together with differences in watershed physiography, land use, and human use and management of water. Responding to this challenge requires an improved understanding of potential changes, and the development of strategies for reducing the risk of harmful impacts. The current toolkit of water quality best management practices (BMPs) is essential to this effort. Relatively little is known, however, about how different types of BMPs will be affected in different regional and watershed settings. In this Task we investigated the effects of warming temperatures and changes in precipitation on BMP performance in watersheds dominated by urban, agricultural and forested land uses. This information helps inform the development of effective, resilient strategies for water quality attainment that perform as required in different watershed settings under a range of future conditions.

Approach

We considered three types of practices: urban, agricultural, and forestry BMPs for reducing runoff and pollutant loading (e.g., N, P, sediment). In each case, Task activities included a review of published literature on the effects of weather and climate variability on BMP performance, and scenario analyses using dynamic watershed models to quantitatively assess the effectiveness of commonly applied management practices under a range of future conditions. Urban BMPs (grey and green) were evaluated using the RHESSys model for a set of 36, block-scale "archetypal" settings representing different development patterns of typical U.S. cities, 11 regional climatic settings, and a range of mid-twenty-first-century scenarios. Agricultural BMPs were evaluated in two watersheds in the Minnesota Corn Belt and the Georgia Coastal Plain with different hydro-climatic settings, under recent conditions (1950-

2005) and multiple potential future mid-century (2030-2059) and late-century (2070-2099) climate scenarios. Forest management practices were evaluated using a combined modeling approach (SWAT, Shade, and QUAL2k) to determine the effectiveness of riparian buffers for reducing the impacts of timber harvest on stream water temperature in Lookout Creek, OR, across a range of potential future changes in air temperature and precipitation. Results were communicated in a set of journal articles describing the potential effects of changes in air temperature and precipitation on BMP performance in different regional and watershed settings.

Findings

Urban BMP simulations with RHESSys suggest regionally variable effects of climate change on the performance of green infrastructure practices for water quantity, water quality, and carbon sequestration (Sarkar et al., 2018). Urban BMPs are especially vulnerable to changes in rainfall patterns. Urban green infrastructure-based practices (e.g., Figure 1) can mitigate most projected future increases in surface runoff, while bioretention can mitigate increased nitrogen yield in 9 of the 11 regional climatic settings evaluated. Simulated changes in carbon balance are small, while local evaporative cooling can be substantial.



Figure 1. (a) Localized urban flooding and (b) an example of a “green” BMP for urban stormwater management.

Agricultural BMP simulations with the Soil and Water Assessment Tool (SWAT) considered the effectiveness of conservation tillage, no-till, vegetated filter strips, grassed waterways, nutrient management, winter cover crops, and drainage water management practices under potential future temperature and precipitation patterns. Results suggest future increases in agricultural source loads of sediment, nitrogen and phosphorous. Most BMPs continue to reduce loads, but removal efficiencies generally decline due to more intense runoff events and biological responses to changes in soil moisture and temperature (Schmidt et al.).

Forest BMP simulations in Lookout Creek, OR, focused on the potential for fully vegetated riparian buffers - beyond current vegetation - to reduce the effects of anticipated future changes in air temperature and precipitation. Maximum stream water temperatures are projected to increase by 17 to 38% (3.3 to 7.4 °C) by the end of this century without changes in buffer shading during thermal stress events (Yonce et al.,). Modest increases in sediment and nutrient loading rates are also projected. Results suggest riparian buffers are effective in preventing stream temperature increases from timber harvesting, but alone will likely not be sufficient to counteract the additional effects of a warming climate. Protection of sensitive aquatic species in this area will likely require additional climate adaptation strategies, such as the protection or provisioning of cool water refugia, to enhance survival during maximum thermal stress events.

Conclusions

The long-term success of water quality protection requires management strategies resilient and performing as required under a wide range of plausible future conditions. This Task examined the response of water quality BMPs to changes in air temperature and precipitation in urban, agricultural, and forest watershed settings. We considered evidence from the scientific literature addressing BMP performance (including mechanistic descriptions of how BMPs function), with model-based scenario simulations of urban, agricultural and forest management BMPs. Results suggest that the coupled effects of higher upland loading to BMPs, and reduced BMP efficiencies will require increased implementation (area/number of practices), resizing, and/or combination of multiple BMPs to meet future water quality goals. Given uncertainty about specific, local scale changes, infrastructure design should emphasize flexibility and robustness across a range of plausible future conditions. Information from this Task about the resilience of different types of BMP can also inform the selection and siting of water quality BMPs for sustainable water quality management

Publications resulting from this research

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Task Title: CIVA-2.11 – Vulnerability and Adaptation Assessments to Support Attainment of the National Water Program Strategy: Response to Climate Change

Task Leads: Britta Bierwagen and Susan Julius

Task Description

The National Water Program (NWP) articulated many goals, strategic actions, and research needs to respond to changing conditions and attain drinking water and water resource standards. Research in this task supported attainment of these standards through application of vulnerability and adaptation assessments in two programmatic areas: monitoring design to detect long-term changes and assess adaptation effectiveness for bioassessment and biocriteria; and implementation of resilient Best Management Practices (BMPs) in water quality attainment plans, particularly for urban stormwater planning.

Background

State and tribal bioassessments of streams and lakes are based on a comparison of impaired and unimpaired sites, but baselines are changing. The lack of contemporaneous biological, thermal and hydrologic data, especially in smaller, headwater, minimally disturbed sites impedes identification and analyses of natural variability and long-term trends. State, tribal, and EPA regional partners have collaborated to set up regionally-based monitoring networks in high quality streams and lakes to inform programs on long-term trends needed to allow reference-based comparisons. These Regional Monitoring Networks (RMNs) provide data on the range of natural variability in high-quality sites and on recovery from extreme events such as droughts and floods. Partners also are deploying continuous water temperature and flow sensors to better characterize the aquatic environment, its variability, and the responses of biota. Data collected at RMN sites help to identify and measure shifts over time in the condition of water resources.

The resilience of stormwater management practices is the second portion of long-term water quality that this task addressed. The Office of Water (OW) has identified a need for improved understanding of the potential impacts of future climate variability on the occurrence and management of stormwater runoff. Additionally, this work supports the Agency FY18-22 Strategic Plan Water goal: “We will modernize and update the aging drinking water, wastewater and stormwater infrastructure that the American public depends on.”

Approach

The goals of the RMNs are to:

- Establish baseline conditions at high-quality stream and lake sites through continuous sensor data;
- Describe the range of natural variability in biological data with respect to thermal and hydrological data;
- Detect long-term trends in environmental conditions; and

- Use vulnerability assessment results to inform protection and restoration decisions.

Monitoring sites have been established in Regions 1, 2, 3, 4, 5, and 7 (Figure 1). Stream sites collect biological, thermal, hydrologic, water quality, and habitat data one or more times per year. Specific parameters include benthic macroinvertebrates, fish, periphyton, continuous air and water temperature, continuous water level data converted to discharge, discrete water chemistry measurements, and visual habitat assessments (USEPA 2016). Lake sites have begun preliminary sampling during the 2018 and 2019 field season at sites across Regions 1, 2, and 5 (Figure 2; USEPA 2019b). Deployment of continuous sensors provides a more complete of the aquatic environment but creates enormous volumes of data that some state and tribal partners are unaccustomed to managing. This project developed R scripts to assist with quality control of the continuous data and facilitate consistent formatting across the diverse set of RMN partners. The development of the lake RMNs required many discussions with partners about parameters and protocols in order to develop consistent recommendations.

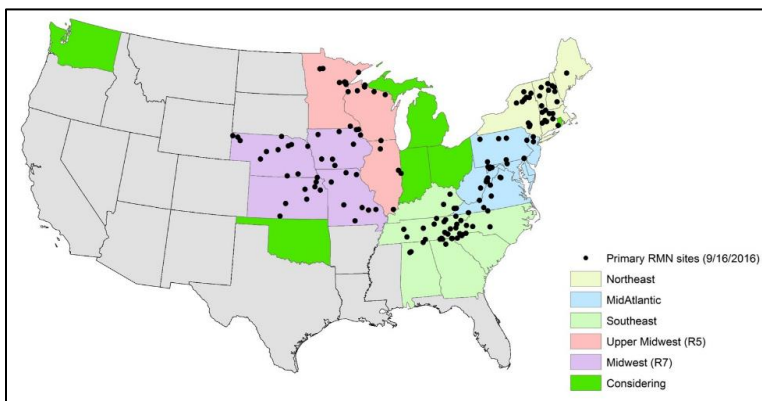


Figure 1. Regional Monitoring Network (RMN) sites in high-quality streams across several EPA Regions.

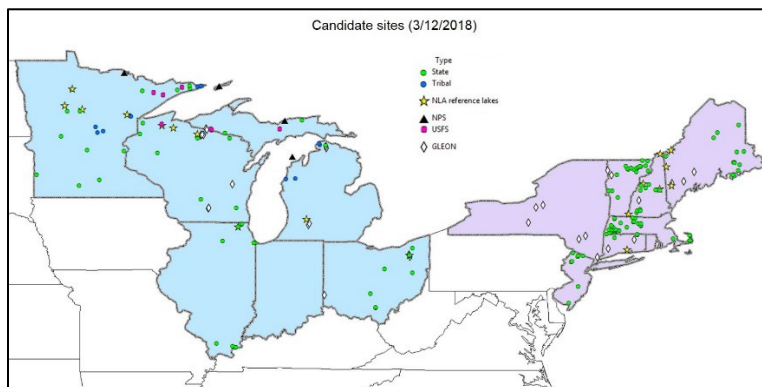


Figure 2. Candidate lake RMN sites across EPA Regions 1, 2, and 5.

The goals of the resilient stormwater management research are to answer the following:

1. How might changes in precipitation and warming temperatures affect performance of conventional stormwater infrastructure and Green Infrastructure (GI) compared to current conditions?
2. How can conventional designs and GI designs be adapted so that a site under future conditions provides the same performance as the site under current conditions?
3. What do the results suggest regarding the adaptation potential of green and gray infrastructure?

To answer these questions, we developed five conceptual sites in detail in different parts of the U.S. representing BMP footprint, volume, and configuration using local and/or state requirements and guidance. We modeled each stormwater management approach under current and a selected set of future conditions. The water quantity and quality performance of the site practices were calculated from modeling results. The site's practices were modified for the future scenarios to achieve the same performance as under current conditions using modeled optimization functions. Modifications targeted resizing the water quality treatment and peak flow control BMPs. We tabulated annual runoff volume, the flow duration curve, and pollutant loads for each site and calculated costs of BMP implementation.

Findings

Data from the RMN sites have been used to inform criteria development for individual states, describe natural variability, and document recovery from extreme events such as droughts and floods (USEPA 2016). For example, data collection at sites in Vermont impacted by Tropical Storm Irene in 2011 illustrate the near-term impacts on the biological community and recovery in community composition after record streamflow (Figure 3; Stamp et al., in review). Data from continuous sensors have been a challenge for some partners in terms of management, quality control, and analysis. The R scripts developed through this project assist with various processes including developing summary statistics and calculating biological metrics. Two tools are currently available on GitHub (Leppo 2019a; Leppo 2019b) and will be downloadable from the "EPA Regional Monitoring Networks (RMNs) for Aquatic Ecosystems" website (www.epa.gov/rmn), along with an R Shiny application to perform quality control and calculate summary statistics on the continuous data through a web browser. Protocols and best practices for lake sampling are compiled in a report and quality assurance project plan for all participants (USEPA 2019a and b).

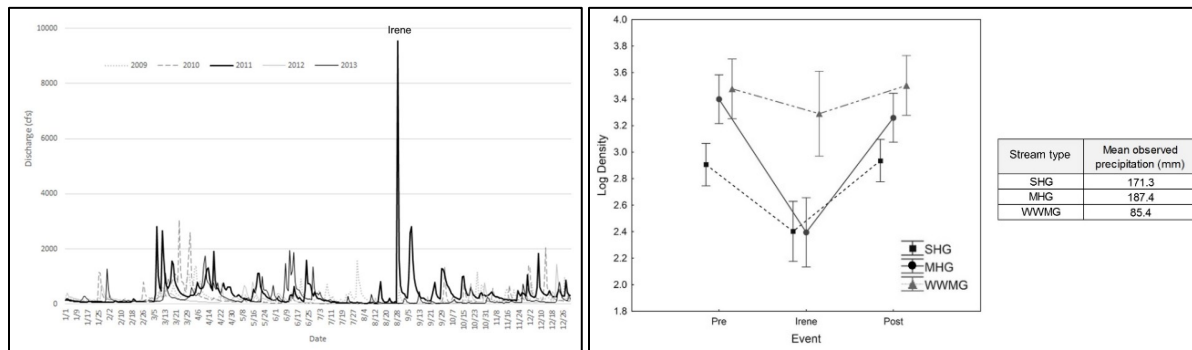


Figure 3. Left panel shows discharge measured at the USGS gage at North River in Shattuckville, MA for the years 2009-2013, including the extreme flow event of Tropical Storm Irene in 2011. Right panel shows benthic macroinvertebrate densities before, shortly after Tropical Storm Irene, and the following year for three different stream types, including upstream of the North River gage in a medium-sized high gradient (MHG) reach. SHG=small, high gradient; WWMG=warm water, moderate gradient.

The analysis of stormwater management practices across a range of conditions shows that overall site export rates of runoff volume and pollutant mass tend to increase under future precipitation conditions despite better volume/mass removal of pollutants. Achieving stormwater control under such conditions will therefore likely require altering BMP design. Controlling large flooding events is the limiting or co-limiting factor in 80% of the adaptation scenarios. Gray infrastructure with detention storage is the most effective for mitigating extreme event volume increases, even though GI has greater flexibility for addressing multiple objectives. Stormwater management that combines gray and green approaches tends to have better cost resiliency overall (Figure 4).

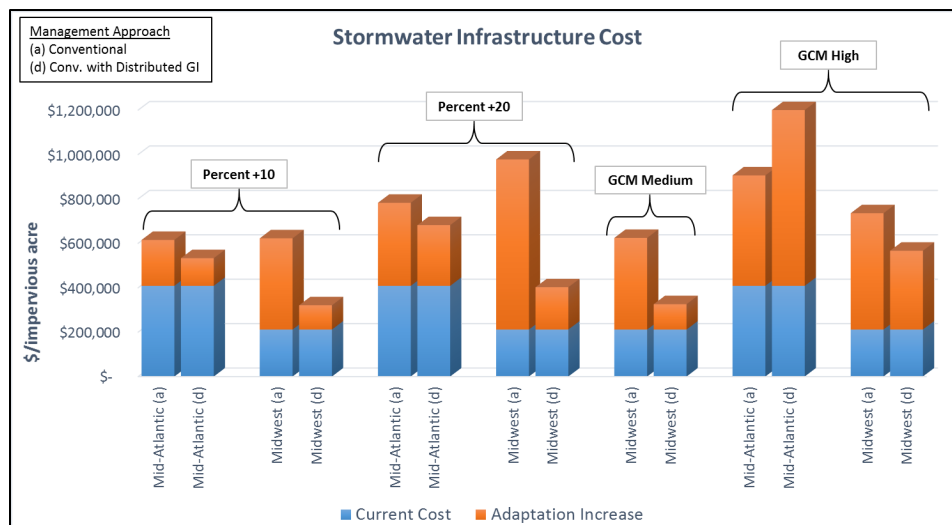


Figure 4. Current cost and BMP adaptation cost increase comparing conventional with resized BMPs to conventional with added distributed BMPs.

Conclusions

The RMN partners continue to collect continuous water temperature and discharge data along with biological samples in order to further our understanding of changing baselines in high-quality, minimally disturbed stream and lake sites. This research has contributed tools and assessments to select sites, analyze data, and further our understanding of changing baselines and vulnerability of aquatic ecosystems.

In terms of stormwater management, this research demonstrates that projected changes in precipitation and temperature could negatively affect BMP performance for both gray and green stormwater management approaches. If stormwater designs are adapted in the future, the most cost resilient approaches may use both gray and green BMPs. If the magnitude of extreme weather events increases dramatically, then gray practices that provide detention storage may have better cost resiliency.

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