Fish Passage Engineering for Climate Change Resiliency

Bibliography

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NCRL subject guide 2021-08
DOI: 10.25923/t2kg-bq49

June 2021

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
Office of Oceanic and Atmospheric Research
NOAA Central Library – Silver Spring, Maryland

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Background & Scope

A National Marine Fisheries Service (NMFS) team of biologists, engineers and climate scientists is working on an appendix to the NOAA Fisheries West Coast Region Anadromous Salmon Passage Design Guidelines. The purpose of the appendix is to assist the fish passage design practitioner to incorporate climate change effects into their design. The NOAA Central Library has created this bibliography in order to identify and acquire peer-reviewed and grey literature that addresses the effects of climate change on civil design, salmonids, natural resource management, and policy. The papers in this bibliography are arranged in alphabetical order by first author and span the years from 1999-2021.

Sources Reviewed

The following sources were consulted and searched in order to create this bibliography: Clarivate's Web of Science, ProQuest's Aquatic Sciences and Fisheries Abstracts, Google Scholar, Dimensions, JSTOR, EBSCO's Academic Search Premier and EconLit, Elsevier's ScienceDirect, BioOne, the Defense Technical Information Center, Science.gov, and open web searching via Google.

References

Albano, C. M., McCarthy, M. I., Dettinger, M. D., & McAfee, S. A. (2021). Techniques for constructing climate scenarios for stress test applications. *Climatic Change,* 164(3-4). https://doi.org/10.1007/s10584-021-02985-6

In this review, we provide guidance on the construction of climate scenarios for stress tests-scenarios that represent disruptive climatic events and can be used to assess the impacts of climate and weather risks at the level of detail that is necessary to identify specific adaptation actions or strategies. While there is a wealth of guidance on scenario-based climate adaptation planning, this guidance typically assumes the selection and use of decadal to century-long time segments of downscaled climate model projections, rather than the creation of a customized scenario depicting a specific extreme event. We address this gap by synthesizing a variety of data sources and analytical techniques for constructing climate scenarios for stress tests that are customized to address specific end-users' needs. We then illustrate the development and application of climate scenarios with a case study that explores water sustainability under changing climate in the Truckee and Carson River basins of California and Nevada. Finally, we assess the potential advantages and disadvantages of the different data sources and analytical techniques described to provide guidance on which are best suited for an intended application based on the system of study, the stakeholders involved, and the resources available. Ultimately, this work is intended to provide the building blocks with which scientist-stakeholder teams can produce their own stress test scenarios to explore place-based weather and climate risks.

Alemaw, B. F., & Sebusang, N. M. (2019). Climate change and adaptation-induced engineering design and innovations in water development projects in Africa. *African Journal of Science, Technology, Innovation and Development,* 11(2), 197-209. https://doi.org/10.1080/20421338.2017.1355601

In this paper, a framework for best practice for incorporating climate change and adaption in Africa is presented from mainly the water resources design and management perspectives to chart systematically ways of incorporating climate change in engineering design of water development projects. This will enable engineers to address the challenges of Africa's vulnerability to climate change and variability which has direct impacts on water availability, access and use which is the source of food and livelihood security for millions of the continent's population. Climate change and variability is projected to affect the hydrological cycle, which, in turn, may alter the balance between water availability leading to uncertainty as to the onset of rainy seasons, dry spells, and more frequent extreme weather events, such as droughts and floods. Using case studies, the authors outline adaptation strategies to be adopted using an integrated approach in the consideration of climate change in engineering design and management of water resources systems that also link to operational aspects of water development projects. The paper also provides a set of suggested best practices in engineering design and innovative approaches to water development involving operation and management of dams and catchments in the face of climate change and variability.

Asian Development Bank. (2020). *Climate Change Adjustments for Detailed Engineering Design of Roads: Experiences from Viet Nam.* Retrieved from https://www.adb.org/sites/default/files/publication/613621/climate-change-design-roads-viet-nam.pdf

Climate change is expected to intensify heavy rainfall and raise global sea levels. Without adaptation and resilience measures, heavier rainfall and higher sea levels are likely to increase river and coastal flooding and erosion risk. Economic analysis of adaptation options lies at the heart of the Asian Development Bank (ADB) project preparation phase. This involves the identification, then the valuation, of engineered and non-engineered adaptation options. This knowledge product explains the rationale and procedures for incorporating allowances for climate change in detailed engineering design (DED). Attention is focused on credible adjustments to extreme rainfall and to mean and high-end sea-level rise, but the same principles and approaches could be extended to other design variables (such as extreme air temperature, evaporation, and wind speed). Although climate hazards are treated separately here, it is important to recognize that these can occur at the same time: within the Asia and Pacific region, tropical cyclones bring heavy rainfall, with high wind speeds, waves, and storm surges. The DED should therefore reflect the possibility of climatedriven changes in multi-hazards at a site. The procedures are demonstrated with worked examples drawn from the Viet Nam road transport sector and peer-reviewed research literature. An accompanying step-by-step manual shows how each calculation is performed. These principles and practices are intended to be transferable to other sectors, regions, and stages of the asset life cycle (from project concept to decommissioning).

Baker, J. P., & Bonar, S. A. (2019). Using a Mechanistic Model to Develop Management Strategies to Cool Apache Trout Streams under the Threat of Climate Change. *North American Journal of Fisheries Management,* 39(5), 849-867. https://doi.org/10.1002/nafm.10337

User-friendly stream temperature models populated with on-site data may help in developing strategies to manage temperatures of individual stream reaches that are subject to climate change. We used the field-tested Stream Segment Temperature model (U.S. Geological Survey) to simulate how altering discharge, groundwater input, channel wetted width, and shade prevents the temperatures of White Mountain, Arizona, stream reaches from exceeding the thermal tolerance of Apache Trout Oncorhynchus apache, both under existing conditions and under a climate change scenario. Simulations suggested increasing shade, either through streamside planting of specific numbers and species of plants or by other means, would be most effective and feasible for cooling the stream reaches we studied. Ponderosa pine Pinus ponderosa and Douglas fir Pseudotsuga menziesii provided the most shade followed in order by Engelman spruce Picea engelmannii, Bebb's willow Salix bebbiana, Arizona alder Alnus oblongifolia, and finally coyote willow Salix exigua. Vegetation survival depends on the appropriateness of site conditions at present and under climate change, and planting in buffer strips minimizes additional water removal from the watershed through evapotranspiration. Alternative shading options, including thick sedge growth, shade cloth, or felled woody vegetation, may be considered when environmental conditions do not support plantings. Increasing groundwater input can cool streams, but additional sources are scarce in the region. Decreasing the width-to-depth ratio would succeed best on reaches with widths greater than 2.0 m. Increasing discharge from upstream may lower water temperature on reaches with an initial discharge greater than 0.5 m(3)/s. Existing models provide suggestions to cool stream reaches. Further development of accessible software packages that incorporate evaporation, fragmentation, and other projected climate change effects into their routines will provide additional tools to help manage climate change effects.

Bamm, M., Dickinson, R., King, C., & Thrasher, B. (2017). *WeatherShift Water Tools: Risk-Based Resiliency Planning for Drainage Infrastructure Design and Rainfall Harvesting*. https://doi.org/10.1061/9780784480618.064

Infrastructure and buildings constructed today will experience significantly different weather patterns over the course of their lifetime due to the impacts of climate change. In order for utility agencies and property developers to plan for these changes, localized data on the projected changes in rainfall patterns is needed. For stormwater management, this data would include changes in rainfall intensity, duration, and frequency, along with correlating updates to existing hydrologic design standards. The WeatherShift flooding tool uses data from 21 global climate models to generate projected rainfall statistics for a range of emission scenarios and future time frames. This data is presented in the form of localized climate change-shifted rainfall Intensity-Duration-Frequency (IDF) curves for use in drainage infrastructure design, such as for sizing storm drain networks, pump stations, and treatment plants. In this paper we discuss how we use data from global climate models and an Argos Analytics-developed tool to construct distributions of future rainfall intensity as a function of rainfall duration and return time, which can then be applied in engineering practice for risk-based resiliency planning of drainage infrastructure. Optimizing infrastructure capacity design enables planning for risk-based adaptations while minimizing lifecycle costs. We also discuss a proposed tool for morphing daily rainfall time series to reflect future climate conditions, which can be used by the TopUp (TM) rainfall harvesting tool to predict future rainfall harvesting scenarios.

Baran, A. A., Moglen, G. E., & Godrej, A. N. (2019). Quantifying Hydrological Impacts of Climate Change Uncertainties on a Watershed in Northern Virginia. *Journal of Hydrologic Engineering,* 24(12). https://doi.org/10.1061/(asce)he.1943-5584.0001860

Forecasted changes to climate were used to model variations in the streamflow characteristics of a northern Virginia catchment. Two emission scenarios were applied from international climate projections along with four general circulation models (GCMs) by using two statistical downscaling methods to drive the hydrological simulations in two future time periods (2046-2065 and 2081-2100). Incorporation of these factors yielded 32 runoff simulation models for a 130-km(2) watershed located in northern Virginia. These models were compared with historical streamflow data from the late 20th century. Changes in streamflow were compared using median, low, and high flows. Results showed a general increase in median flows in both the mid- and late 21st century. Low flows were projected to decrease, whereas high flows were projected to increase, creating a larger range between low flows and high flows. In addition, statistical tests were conducted to identify the main factors that affected variations in future climate projections. The choice of the downscaling method emerged as the main source of uncertainty. This research quantifies the impacts of climate change as well as uncertainties within climate change projections for regional water resources. Considering the essential role of this watershed for water supply in northern Virginia, the findings of this study illustrate likely impacts of climate change on water supply reliability, supporting climate resiliency in the study area.

Bastos, G., Matos, J., & Neves, J. (2020). Evaluation of the Hydraulic Design of Culverts Under a Climate Change Scenario: A Preliminary Analysis of Road Case Studies in Southern Portugal. In *Advances in Natural Hazards and Hydrological Risks: Meeting the Challenge, Nathaz' 19.* F. Fernandes, A. Malheiro, & H. I. Chamine (Eds.), (pp. 177-180) https://doi.org/10.1007/978-3-030-34397-2_34

The present work aims to contribute to the study of current capacity of culverts associated to transportation infrastructures, under a climate change scenario. The records of annual maximum daily precipitation were analysed for two meteorological stations, allowing to estimate such precipitation for both stations, namely through the adjustment of a statistical law for a return period of 100 years. Design precipitations were then determined through a methodology that makes use of annual maximum daily precipitation estimation. Through hydrological and hydraulic methodologies frequently used in hydraulic and drainage projects in Portugal, eight culverts were evaluated. The hydraulic analysis led to the conclusion that three out of eight culverts had an insufficient flow rate capacity. According to those results, it is not possible to conclude that climate change is directly influencing the adequacy of such culverts, in terms of flow rate capacity. Nevertheless, it seems reasonable to expect that a considerable number of culverts may no longer be suitable in terms of flow rate capacity, resulting in a potential high number of critical points in the Portuguese road network, jeopardizing the safety of the transportation infrastructure and its users.

Battin, J., Wiley, M. W., Ruckelshaus, M. H., Palmer, R. N., Korb, E., Bartz, K. K., & Imaki, H. (2007). Projected impacts of climate change on salmon habitat restoration. *Proceedings of the National Academy of Sciences,* 104(16), 6720. https://doi.org/10.1073/pnas.0701685104

Throughout the world, efforts are under way to restore watersheds, but restoration planning rarely accounts for future climate change. Using a series of linked models of climate, land cover, hydrology, and salmon population dynamics, we investigated the impacts of climate change on the effectiveness of proposed habitat restoration efforts designed to recover depleted Chinook salmon populations in a Pacific Northwest river basin. Model results indicate a large negative impact of climate change on freshwater salmon habitat. Habitat restoration and protection can help to mitigate these effects and may allow populations to increase in the face of climate change. The habitat deterioration associated with climate change will, however, make salmon recovery targets much more difficult to attain. Because the negative impacts of climate change in this basin are projected to be most pronounced in relatively pristine, high-elevation streams where little restoration is possible, climate change and habitat restoration together are likely to cause a spatial shift in salmon abundance. River basins that span the current snow line appear especially vulnerable to climate change, and salmon recovery plans that enhance lower-elevation habitats are likely to be more successful over the next 50 years than those that target the higher-elevation basins likely to experience the greatest snow–rain transition.

Beechie, T., & Imaki, H. (2014). Predicting natural channel patterns based on landscape and geomorphic controls in the Columbia River basin, USA. *Water Resources Research,* 50(1), 39-57. https://doi.org/10.1002/2013wr013629

Based on known relationships of slope, discharge, valley confinement, sediment supply, and sediment caliber in controlling channel patterns, we developed multivariate models to predict natural channel patterns across the 674,500 km(2) Columbia River basin, USA. We used readily available geospatial data sets to calculate reach slopes, 2 year flood discharge, and valley confinement, as well as to develop hypothesized landscape-level surrogates for sediment load and caliber (relative slope, percent of drainage area in alpine terrain, and percent of drainage area in erosive fine-grained lithologies). Using a support vector machine (SVM) classifier, we found that the four channel patterns were best distinguished by a model including all variables except valley confinement (82% overall accuracy). We then used that model to predict channel pattern for the entire basin and found that the spatial distribution of straight, meandering, anabranching, and braided patterns were consistent with regional topography and geology. A simple slope-discharge model distinguished meandering channels from all other channel patterns, but did not clearly distinguish braided from straight channels (68% overall accuracy). Addition of one or more of the hypothesized sediment supply surrogates improved prediction accuracy by 4-14% over slope and discharge alone. Braided and straight channels were most clearly distinguished on an axis of relative slope, whereas braided and anabranching channels were most clearly distinguished by adding percent alpine area to the model.

Beechie, T., Imaki, H., Greene, J., Wade, A., Wu, H., Pess, G., . . . Mantua, N. (2013). Restoring Salmon Habitat for a Changing Climate. *River Research and Applications,* 29(8), 939-960. https://doi.org/10.1002/rra.2590

An important question for salmon restoration efforts in the western USA is "How should habitat restoration plans be altered to accommodate climate change effects on stream flow and temperature?" We developed a decision support process for adapting salmon recovery plans that incorporates (1) local habitat factors limiting salmon recovery, (2) scenarios of climate change effects on stream flow and temperature, (3) the ability of restoration actions to ameliorate climate change effects, and (4) the ability of restoration actions to increase habitat diversity and salmon population resilience. To facilitate the use of this decision support framework, we mapped scenarios of future stream flow and temperature in the Pacific Northwest region and reviewed literature on habitat restoration actions to determine whether they ameliorate a climate change effect or increase life history diversity and salmon resilience. Under the climate change scenarios considered here, summer low flows decrease by 35-75% west of the Cascade Mountains, maximum monthly flows increase by 10-60% across most of the region, and stream temperatures increase between 2 and 6°C by 2070-2099. On the basis of our literature review, we found that restoring floodplain connectivity, restoring stream flow regimes, and re-aggrading incised channels are most likely to ameliorate stream flow and temperature changes and increase habitat diversity and population resilience. By contrast, most restoration actions focused on in-stream rehabilitation are unlikely to ameliorate climate change effects. Finally, we illustrate how the decision support process can be used to evaluate whether climate change should alter the types or priority of restoration actions in a salmon habitat restoration plan.

Benjankar, R., Tonina, D., McKean, J. A., Sohrabi, M. M., Chen, Q. W., & Vidergar, D. (2018). Dam operations may improve aquatic habitat and offset negative effects of climate change. *Journal of Environmental Management,* 213, 126-134. https://doi.org/10.1016/j.jenvman.2018.02.066

Dam operation impacts on stream hydraulics and ecological processes are well documented, but their effect depends on geographical regions and varies spatially and temporally. Many studies have quantified their effects on aquatic ecosystem based mostly on flow hydraulics overlooking stream water temperature and climatic conditions. Here, we used an integrated modeling framework, an ecohydraulics virtual watershed, that links catchment hydrology, hydraulics, stream water temperature and aquatic habitat models to test the hypothesis that reservoir management may help to mitigate some impacts caused by climate change on downstream flows and temperature. To address this hypothesis we applied the model to analyze the impact of reservoir operation (regulated flows) on Bull Trout, a cold water obligate salmonid, habitat, against unregulated flows for dry, average, and wet climatic conditions in the South Fork Boise River (SFBR), Idaho, USA.

Bieniek, P. A., Bhatt, U. S., Thoman, R. L., Angeloff, H., Partain, J., Papineau, J., . . . Gens, R. (2012). Climate Divisions for Alaska Based on Objective Methods. *Journal of Applied Meteorology and Climatology,* 51(7), 1276-1289. https://doi.org/10.1175/JAMC-D-11-0168.1

Alaska encompasses several climate types because of its vast size, high-latitude location, proximity to oceans, and complex topography. There is a great need to understand how climate varies regionally for climatic research and forecasting applications. Although climate-type zones have been established for Alaska on the basis of seasonal climatological mean behavior, there has been little attempt to construct climate divisions that identify regions with consistently homogeneous climatic variability. In this study, cluster analysis was applied to monthly-average temperature data from 1977 to 2010 at a robust set of weather stations to develop climate divisions for the state. Mean-adjusted Advanced Very High Resolution Radiometer surface temperature estimates were employed to fill in missing temperature data when possible. Thirteen climate divisions were identified on the basis of the cluster analysis and were subsequently refined using local expert knowledge. Divisional boundary lines were drawn that encompass the grouped stations by following major surrounding topographic boundaries. Correlation analysis between station and gridded downscaled temperature and precipitation data supported the division placement and boundaries. The new divisions north of the Alaska Range were the North Slope, West Coast, Central Interior, Northeast Interior, and Northwest Interior. Divisions south of the Alaska Range were Cook Inlet, Bristol Bay, Aleutians, Northeast Gulf, Northwest Gulf, North Panhandle, Central Panhandle, and South Panhandle. Correlations with various Pacific Ocean and Arctic climatic teleconnection indices showed numerous significant relationships between seasonal division average temperature and the Arctic Oscillation, Pacific–North American pattern, North Pacific index, and Pacific decadal oscillation.

Bisson, P. A., Dunham, J. B., & Reeves, G. H. (2009). Freshwater Ecosystems and Resilience of Pacific Salmon: Habitat Management Based on Natural Variability. *Ecology and Society,* 14(1). Retrieved from http://www.ecologyandsociety.org/vol14/iss1/art45/

In spite of numerous habitat restoration programs in fresh waters with an aggregate annual funding of millions of dollars, many populations of Pacific salmon remain significantly imperiled. Habitat restoration strategies that address limited environmental attributes and partial salmon life-history requirements or approaches that attempt to force aquatic habitat to conform to idealized but ecologically unsustainable conditions may partly explain this lack of response. Natural watershed processes generate highly variable environmental conditions and population responses, i.e., multiple life histories, that are often not considered in restoration. Examples from several locations underscore the importance of natural variability to the resilience of Pacific salmon. The implication is that habitat restoration efforts will be more likely to foster salmon resilience if they consider processes that generate and maintain natural variability in fresh water. We identify three specific criteria for management based on natural variability: the capacity of aquatic habitat to recover from disturbance, a range of habitats distributed across stream networks through time sufficient to fulfill the requirements of diverse salmon life histories, and ecological connectivity. In light of these considerations, we discuss current threats to habitat resilience and describe how regulatory and restoration approaches can be modified to better incorporate natural variability.

Bourdin, D. R., Fleming, S. W., & Stull, R. B. (2012). Streamflow Modelling: A Primer on Applications, Approaches and Challenges. *Atmosphere-Ocean,* 50(4), 507-536. https://doi.org/10.1080/07055900.2012.734276

This article examines the current practice of streamflow modelling, a field under development for over a century. A sample of the wide range of assessment and planning applications of streamflow models is presented. The diversity in the use of these models is mirrored in the diversity of model complexity, and modelling approaches ranging from empirical to physically based and from lumped to fully distributed are described with examples. Predictions derived from hydrological models are subject to many sources of error; these are discussed along with methods for error minimization or anticipation. Model error is generally quantified using an ensemble of forecasts meant to sample the range of predictive uncertainty. This ensemble can be used to generate reliable probabilistic forecasts of hydrological quantities if all sources of error are accounted for. To date, applications of ensemble methods in streamflow forecasting have typically focused on only one or two error sources. A challenge will be to develop ensemble streamflow forecasts that sample a wider range of predictive uncertainty.

British Columbia Ministry of Transportation and Infrastructure. (2019). *Resilient Infrastructure Engineering Design - Adaptation to the Impacts of Climate Change and Weather Extremes* (T-04/19). Retrieved from https://www2.gov.bc.ca/assets/gov/driving-and-transportation/transportation-infrastructure/engineering-standards-and-guidelines/technical-circulars/2019/t04-19.pdf

This technical circular supersedes Technical Circular T-06/15 - Climate Change and Extreme Weather Event Preparedness and Resilience in Engineering Infrastructure Design. Given the potential for climate change to impact transportation infrastructure in BC, it is prudent to develop directives and guidance for incorporating climate adaptation into engineering designs provided to the BC Ministry of Transportation and Infrastructure. Thus, the Ministry requires engineering design work to evaluate risk and include adaptation measures to the impacts of future climate change, weather extremes and climate-related events, as well as changes in average climate conditions. This policy applies to all new projects, as well as rehabilitation and maintenance projects. Supporting resources for this policy, such as practice guidance, adaptation project-examples and risk assessment methods, can be obtained from sources such as professional associations. Climate information can be obtained from climate resource providers. Some of these resources are found on the BCMoTI Climate Change and Adaptation website. This policy aligns with the BC Climate Action Plan - in developing strategies to help BC adapt to the effects of climate changes. And therefore, the Ministry will continue to provide a provincial transportation system that is resilient, reliable and efficient regardless of unfolding impacts of climate change.

Byun, K., & Hamlet, A. F. (2020). A risk-based analytical framework for quantifying non-stationary flood risks and establishing infrastructure design standards in a changing environment. *Journal of Hydrology,* 584. https://doi.org/10.1016/j.jhydrol.2020.124575

In a rapidly changing environment, analysis of risks associated with non-stationary hydroclimatic extremes has many important implications for resilient and sustainable water resources management, including the evaluation of risk for existing systems and the design of new infrastructure. This study develops a new risk-based analytical framework called the Non-Stationary Monte-Carlo (NSMC) to better address various problems associated with non-stationarity of hydrologic extremes. Current approaches in the literature evaluating non-stationary Probability Distribution Functions (PDFs) of extremes events commonly use trend extension or multivariate analysis based on observed data, which often fail to account for larger changes in the future. To avoid these problems, NSMC explicitly accounts for the projected changes in hydroclimatic extremes by analyzing the changing PDFs of extremes for each future year based on statistically downscaled climate projections and hydrologic simulations. Using Monte Carlo techniques, NSMC generates a Super Ensemble (SE) of extremes, the statistics of which can be readily applied to various problems in non-stationary flood frequency analysis. For example, we show that the estimation of design standards based on Design Life Level (DLL) or Average Risk of Failure (ARF) metrics can be reduced to a simple look-up process of quantiles in the SE of extremes. A case study analyzing extreme high streamflow and a hypothetical levee design for the Wabash basin (IN, USA) demonstrates the applicability of NSMC to real-world flood risk problems. Furthermore, this study also shows an example case of using NSMC to identify cost-effective design standards for new infrastructure combining future changing risk of failure, project design lifespan, and present value of future replacement costs.

Cai, X. W., Ye, F., & Matin, G. N. (2021). Data-driven-based determination of influential parameters on local energy loss of slope-tapered culvert. *Journal of Hydroinformatics,* 23(1), 16-27. https://doi.org/10.2166/hydro.2020.189

Local energy loss is among the essential parameters of culvert design, in which uncertainty and nonlinearity is controversial. In the present study, seven models were developed with the aid of the experimental data of slope-tapered culverts, and the efficiency of gene expression programing and Gaussian process regression as a kernel-based approach was assessed in predicting the entrance loss coefficient of a slope-tapered culvert. Also, one-at-a-time (OAT) sensitivity analysis was performed to determine the impact of input parameters. The results of both GEP and GPR methods with the performance criteria of R = 0.847, DC = 0.777, RMSE = 0.2 and R = 0.76, DC = 0.718, RMSE = 0.25 showed that the model with input parameters of Froude number (Fr), ratio of headwater to culvert diameter (H-w/D) and ratio of reducer length to barrel length (L-r/L) is the superior model. Although the accuracy of GEP method was slightly higher than GPR, obtained results proved the capability of the applied methods (i.e., high correlation coefficient (R) and coefficient of determination R-2 (DC) and low RMSE). Furthermore, OAT sensitivity analysis revealed that Froude number has the most impact on local loss coefficient and could cause a significant increment in model efficiency.

California Department of Water Resources Climate Change Program. (2020). *Climate Action Plan Phase III: Climate Change Adaptation Plan*. Retrieved from https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Climate-Change-Program/Climate-Action-Plan/Files/Adaptation_Plan.pdf

As part of a three-phase process known as the Climate Action Plan (CAP), the California Department of Water Resources (DWR) seeks to reduce greenhouse gas emissions (CAP – Phase I), conduct consistent and rigorous climate change analyses within its programs and projects (CAP – Phase II), and complete a climate change vulnerability assessment and develop and implement an adaptation process to protect staff, business operations and assets (CAP – Phase III). This document presents the first iteration of the DWR Climate Change Adaptation Plan, which is the last step of CAP – Phase III. This Adaptation Plan creates a foundation from which DWR can adapt to climate change and improve its resilience. The first section introduces concepts, framing, and principles of adaptation and how to use these to support adaptation monitoring, evaluation, and reflection as the Adaptation Plan progresses. The second section describes actions to reduce the vulnerability of four assets identified in the DWR Climate Change Vulnerability Assessment. The third section presents other efforts by DWR that promote climate adaptation at local and regional levels throughout California. And the fourth section concludes with additional efforts required to meet DWR's climate change challenges.

Carlson, A. K., Taylor, W. W., Schlee, K. M., Zorn, T. G., & Infante, D. M. (2017). Projected impacts of climate change on stream salmonids with implications for resilience-based management. *Ecology of Freshwater Fish,* 26(2), 190-204. https://doi.org/10.1111/eff.12267

The sustainability of freshwater fisheries is increasingly affected by climate warming, habitat alteration, invasive species and other drivers of global change. The State of Michigan, USA, contains ecologically, socioeconomically valuable coldwater stream salmonid fisheries that are highly susceptible to these ecological alterations. Thus, there is a need for future management approaches that promote resilient stream ecosystems that absorb change amidst disturbances. Fisheries professionals in Michigan are responding to this need by designing a comprehensive management plan for stream brook charr (Salvelinus fontinalis), brown trout (Salmo trutta) and rainbow trout (Oncorhynchus mykiss) populations. To assist in developing such a plan, we used stream-specific regression models to forecast thermal habitat suitability in streams throughout Michigan from 2006 to 2056 under different predicted climate change scenarios. As baseflow index (i.e., relative groundwater input) increased, stream thermal sensitivity (i.e., relative susceptibility to temperature change) decreased. Thus, the magnitude of temperature warming and frequency of thermal habitat degradation were lowest in streams with the highest baseflow indices. Thermal habitats were most suitable in rainbow trout streams as this species has a wider temperature range for growth (12.0-22.5 degrees C) compared to brook charr (11.0-20.5 degrees C) and brown trout (12.0-20.0 degrees C). Our study promotes resilience-based salmonid management by providing a methodology for stream temperature and thermal habitat suitability prediction. Fisheries professionals can use this approach to protect coldwater habitats and drivers of stream cooling and ultimately conserve resilient salmonid populations amidst global change.

CECW-EC US Army Corps of Engineers. (2018). Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects. *Engineering and Construction Bulletin,* 14. Retrieved from https://www.wbdg.org/FFC/ARMYCOE/COEECB/ecb_2018_14_rev_1.pdf

This Engineering and Construction Bulletin (ECB) reissues and updates the policy in ECB 2016-25 (reference a), Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects. This ECB is effective immediately and applies to all hydrologic analyses supporting planning and engineering decisions having an extended decision time frame (i.e., not for short-term water management decisions). It provides guidance for incorporating climate change information in hydrologic analyses in accordance with the USACE overarching climate preparedness and resilience policy and ER 1105-2-101 (reference l) . This policy requires consideration of climate change in all current and future studies to reduce vulnerabilities and enhance the resilience of communities. Hence, consideration of climate change should occur early enough in the SMART planning process to inform plan formulation, evaluation, and selection of the tentatively selected plan.

Cenderelli, D. A., Clarkin, K., Gubernick, R. A., & Weinhold, M. (2011). Stream Simulation for Aquatic Organism Passage at Road-Stream Crossings. *Transportation Research Record*(2203), 36-45. https://doi.org/10.3141/2203-05

Historically, road stream crossing structures were designed on the basis of the hydraulic capacity of the structure for a specific design flood without consideration of aquatic species or the swimming and jumping abilities of a single target fish species and life stage during its migration, and ignored the movement needs of other adult fish, juvenile fish, and aquatic organisms occupying the stream. Hydraulic designs typically constrict the channel, create flow hydraulics and channel conditions that are markedly dissimilar from those in the natural channel, and impede the movement of most other nontarget fish and aquatic organisms along the stream corridor. The stream simulation approach for designing road stream crossing structures was recently adopted by the U.S. Department of Agriculture Forest Service as a pragmatic and sustainable long-term solution to maintain passage for all aquatic organisms at all life stages at road stream crossings while meeting vehicle transportation objectives. This study shows how the stream simulation design process integrates fluvial geo-morphology concepts with engineering principles to design a natural and dynamic channel through the road stream crossing structure. The premise of stream simulation is that the creation of channel dimensions and characteristics similar to those in the adjacent natural channel will enable fish and other aquatic organisms to experience no greater difficulty moving through the structure than if there were no crossing. Stream simulation channels are designed to adjust laterally and vertically to a wide range of floods and sediment or wood inputs without compromising the movement needs of fish and other aquatic organisms or the hydraulic capacity of the structure.

Chang, H. J., & Jung, I. W. (2010). Spatial and temporal changes in runoff caused by climate change in a complex large river basin in Oregon. *Journal of Hydrology,* 388(3-4), 186-207. https://doi.org/10.1016/j.jhydrol.2010.04.040

We estimated potential changes in annual, seasonal, and high and low runoff and associated uncertainty in the 218 sub-basins of the Willamette River basin of Oregon for the 2040s and the 2080s. The US Geological Survey's Precipitation-Runoff Modeling System (PRMS) was calibrated and validated for representative river basins between 1973 and 2006. A regionalization method and GIS analysis determined the PRMS model parameters for ungauged basins. We used a combination of eight general circulation models (GCMs) and two emission scenarios downscaled to 1/16 degrees resolution to estimate spatial and temporal changes in future runoff at a sub-basin scale. The seasonal variability of runoff is projected to increase consistently with increases in winter flow and decreases in summer flow. These trends are amplified under the A1B emission scenario by the end of the 21st century with increases in top 5% flow and decreases in 7-day low flow. The ratio of snow water equivalent to precipitation declined consistently throughout the basins extending into the Cascade Range. The center timing of runoff, the day when half of the water-year flow has passed, is projected to occur earlier in the water year. Snowmelt-dominated basins exhibit large reductions in summer flow in response to increased temperature, while rainfall-dominated basins show large increases in winter flow in response to precipitation change. The spatial and temporal variability of runoff may increase in the future, but the direction and magnitude of these changes depend on sub-basin characteristics such as elevation and geology. Streams flowing from High Cascade basins that contain a large component of groundwater are projected to sustain summer flows, although the uncertainty associated with future projections is high. The main source of uncertainty stems from GCM structure rather than emission scenarios or hydrologic model parameters, but the hydrologic model parameter uncertainty for projecting summer runoff and 7-day low flow is relatively high for Western Cascade basins.

Chang, H. J., & Psaris, M. (2013). Local landscape predictors of maximum stream temperature and thermal sensitivity in the Columbia River Basin, USA. *Science of the Total Environment,* 461, 587-600. https://doi.org/10.1016/j.scitotenv.2013.05.033

Stream temperature regimes are important determinants of the health of lotic ecosystems, and a proper understanding of the landscape factors affecting stream temperatures is needed for water managers to make informed decisions. We analyzed spatial patterns of thermal sensitivity (response of stream temperature to changes in air temperature) and maximum stream temperature for 74 stations in the Columbia River basin, to identify landscape factors affecting these two indices of stream temperature regimes. Thermal sensitivity (TS) is largely controlled by distance to the Pacific Coast, base flow index, and contributing area. Maximum stream temperature (Tmax) is mainly controlled by base flow index, percent forest land cover, and stream order. The analysis of four different spatial scales - relative contributing area (RCA) scale, RCA buffered scale, 1 km upstream RCA scale, and 1 km upstream buffer scale - yield different significant factors, with topographic factors such as slope becoming more important at the buffer scale analysis for TS. Geographically weighted regression (GWR), which takes into account spatial non-stationary processes, better predicts the spatial variations of TS and Tmax with higher R-2 and lower residual values than ordinary least squares (OLS) estimates. With different coefficient values over space, GWR models explain approximately up to 62% of the variation in TS and Tmax. Percent forest land cover coefficients had both positive and negative values, suggesting that the relative importance of forest changes over space. Such spatially varying GWR coefficients are associated with land cover, hydroclimate, and topographic variables. OLS estimated regression residuals are positively autocorrelated over space at the RCA scale, while the GWR residuals exhibit no spatial autocorrelation at all scales. GWR models provide useful additional information on the spatial processes generating the variations of TS and Tmax, potentially serving as a useful tool for managing stream temperature across multiple scales.

Chegwidden, O. S., Rupp, D. E., & Nijssen, B. (2020). Climate change alters flood magnitudes and mechanisms in climatically-diverse headwaters across the northwestern United States. *Environmental Research Letters,* 15(9). https://doi.org/10.1088/1748-9326/ab986f

Flooding caused by high streamflow events poses great risk around the world and is projected to increase under climate change. This paper assesses how climate change will alter high streamflow events by changing both the prevalence of different driving mechanisms (i.e. 'flood generating processes') and the magnitude of differently generated floods. We present an analysis of simulated changes in high streamflow events in selected basins in the hydroclimatically diverse Pacific Northwestern United States, classifying the events according to their mechanism. We then compare how the different classes of events respond to changes in climate at the annual scale. In a warmer future, high flow events will be caused less frequently by snowmelt and more frequently by precipitation events. Also, precipitation-driven high flow events are more sensitive to increases in precipitation than are snowmelt-driven high flow events, so the combination of the increase in both frequency and magnitude of precipitation-driven high flow events leads to higher flood likelihood than under each change alone. Our comparison of the results from two emissions pathways shows that a reduction in global emissions will limit the increase in magnitude and prevalence of these precipitation-driven events.

Cheng, Y. F., Voisin, N., Yearsley, J. R., & Nijssen, B. (2020). Reservoirs Modify River Thermal Regime Sensitivity to Climate Change: A Case Study in the Southeastern United States. *Water Resources Research,* 56(6). https://doi.org/10.1029/2019wr025784

Seasonal thermal stratification in reservoirs changes the thermal regime of regulated river systems as well as stream temperature responses to climate change. Cold releases from the reservoir hypolimnion can depress downstream river temperature during warm seasons. Recent large-scale climate change studies on stream temperature have largely ignored reservoir thermal stratification. In this study, we used established models to develop a framework which considers water demand and reservoir regulation with thermal stratification and applied this model framework to the southeastern United States. About half of all 271 reservoirs in our study area retain strong thermal stratification by the 2080s (2070-2099) under RCP8.5 even as median residence times decrease to 60 days from 69 days in the historic period (1979-2010). Reservoir impacts on downstream temperatures become slightly weaker in the future because of higher air temperature and stronger solar radiation. We defined a "cooling potential" to quantify the thermal energy that a water body can absorb before exceeding a water temperature threshold. In the future, higher river temperatures will reduce the cooling potential for all river segments, but more so for river segments minimally impacted by thermal stratification. Reservoir impacts on cooling potential remain strong for river segments downstream of reservoirs with strong thermal stratification. We conducted a sensitivity analysis to evaluate the robustness of our findings to errors in the hydrological simulations. Although river segments subject to reservoir regulation are more sensitive to errors in hydrology than those without regulation impacts, our overall findings do not materially change due to these errors. Plain Language Summary River temperature is influenced by both climate change and human activities, especially dam regulation. Large dams impound deep reservoirs where only the top layer is warmed while the bottom stays cold. This phenomenon, with colder, heavier water at the bottom and warmer, lighter water on top, is known as thermal stratification. Large reservoirs usually release water from the bottom and thus cool downstream river temperature in the summer. In this study, we use computer models to simulate river flow and temperature while considering the influence of reservoir regulation and thermal stratification. Thermal stratification will strengthen for about half of the 271 reservoirs in the southeastern United States, but the cold outflow warms up faster due to global warming. Environmental agencies regulate maximum allowable river temperature, constraining a river's ability to provide cooling water for power plants. The cool release from the bottom layer provides more downstream cooling potential, that is, the energy that a river can absorb before exceeding a water temperature threshold, than would be possible in an unregulated river. In the future, the cooling potential will decrease as the climate warms, especially in unregulated rivers. Although our models are subject to errors, these errors do not change our overall findings.

Clifton, C. F., Day, K. T., Luce, C. H., Grant, G. E., Safeeq, M., Halofsky, J. E., & Staab, B. P. (2018). Effects of climate change on hydrology and water resources in the Blue Mountains, Oregon, USA. *Climate Services,* 10, 9-19. https://doi.org/10.1016/j.cliser.2018.03.001

In the semi-arid environment of the Blue Mountains, Oregon (USA), water is a critical resource for both ecosystems and human uses and will be affected by climate change in both the near- and long-term. Warmer temperatures will reduce snowpack and snow-dominated watersheds will transition to mixed rain and snow, while mixed rain and snow dominated watersheds will shift towards rain dominated. This will result in high flows occurring more commonly in late autumn and winter rather than spring, and lower low flows in summer, phenomena that may already be occurring in the Pacific Northwest. Higher peak flows are expected to increase the frequency and magnitude of flooding, which may increase erosion and scouring of the streambed and concurrent risks to roads, culverts, and bridges. Mapping of projected peak flow changes near roads gives an opportunity to mitigate these potential risks. Diminished snowpack and low summer flows are expected to cause a reduction in water supply for aquatic ecosystems, agriculture, municipal consumption, and livestock grazing, although this effect will not be as prominent in areas with substantial amounts of groundwater. Advanced planning could help reduce conflict among water users. Responding pro-actively to climate risks by improving current management practices, like road design and water management as highlighted here, may be among the most efficient and effective methods for adaptation.

Cohen, J. S., Zeff, H. B., & Herman, J. D. (2020). Adaptation of Multiobjective Reservoir Operations to Snowpack Decline in the Western United States. *Journal of Water Resources Planning and Management,* 146(12). https://doi.org/10.1061/(asce)wr.1943-5452.0001300

Long-term snowpack decline is among the best-understood impacts of climate change on water resources systems. This trend has been observed for decades and is projected to continue even in climate projections in which total runoff volumes do not change significantly. For basins in which snowpack has historically provided intra-annual water storage, snowpack decline creates several issues that may require adaptation to infrastructure, operations, or both. This study develops an approach to analyze vulnerabilities and adaptations specifically focused on the challenge of snowpack decline, using the northern California reservoir system as a case study. We first introduce an open-source daily time-step simulation model of this system, which is validated against historical observations of operations. Multiobjective vulnerabilities to snowpack decline are then examined using a set of downscaled climate scenarios to capture the physically based effects of rising temperatures. A statistical analysis shows that the primary impacts include water supply shortage and lower reservoir storage resulting from the seasonal shift in runoff timing. These challenges identified from the vulnerability assessment inform proposed adaptations to operations to maintain multiobjective performance across the ensemble of plausible future scenarios, which include other uncertain hydrologic changes. To adapt seasonal reservoir management without the cost of additional infrastructure, we specifically propose and test adaptations that parameterize the structure of existing operating policies: a dynamic flood control rule curve and revised snowpack-to-streamflow forecasting methods to improve seasonal runoff predictability given declining snowpack. These adaptations are shown to mitigate the majority of vulnerabilities caused by snowpack decline across the scenario ensemble, with remaining opportunities for improvement using formal policy search and dynamic adaptation techniques. The coupled approach to vulnerability assessment and adaptation is generalizable to other snowmelt-dominated water resources systems facing the loss of seasonal storage due to rising temperatures.

Committee on Adaptation to a Changing Climate. (2015). *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate* (J. R. Olsen Ed.): American Society of Civil Engineers. https://doi.org/10.1061/9780784479193

Adapting Infrastructure and Civil Engineering Practice to a Changing Climate presents an accurate discussion of the potential significance of climate change to engineering practice. Although considerable evidence indicates that the climate is changing, significant uncertainty exists regarding the location, timing, and magnitude of this change over the lifetime of infrastructure. Practicing engineers are faced with the dilemma of balancing future needs for engineered infrastructure with the risks posed by the effects of climate change on long-term engineering projects. The gap between climate science and engineering practice somehow must be bridged. This report identifies the technical requirements and civil engineering challenges raised by adaptation to a changing climate.

Topics include: review of climate science for engineering practice; incorporating climate science into engineering practice; civil engineering sectors that might be affected by climate change; needs for research, development, and demonstration projects; and summary, conclusions, and recommendations. Three appendixes illustrate different engineering approaches to assessing or preparing for climate change.

Practitioners, researchers, educators, and students of civil engineering, as well as government officials and allied professionals, will be fascinated by this discussion of the trade-offs between the expenses of increasing system reliability and the potential costs and consequences of failure to future generations.

Connell-Buck, C. R., Medellin-Azuara, J., Lund, J. R., & Madani, K. (2011). Adapting California's water system to warm vs. dry climates. *Climatic Change,* 109, 133-149. https://doi.org/10.1007/s10584-011-0302-7

This paper explores the independent and combined effects of changes in temperature and runoff volume on California's water supply and potential water management adaptations. Least-cost water supply system adaptation is explored for two climate scenarios: 1) warmer-drier conditions, and 2) warmer conditions without change in total runoff, using the CALVIN economic-engineering optimization model of California's intertied water supply system for 2050 water demands. The warm-dry hydrology was developed from downscaled effects of the GFDL CM2.1 (A2 emissions scenario) global climate model for a 30-year period centered at 2085. The warm-only scenario was developed from the warm-dry hydrology, preserving its seasonal runoff shift while maintaining mean annual flows from the historical hydrology. This separates the runoff volume and temperature effects of climate change on water availability and management adaptations. A warmer climate alone reduces water deliveries and increases costs, but much less than a warmer-drier climate, if the water supply system is well managed. Climate changes result in major changes in reservoir operations, cyclic storage of groundwater, and hydropower operations.

Coulthard, T. J., Ramirez, J., Fowler, H. J., & Glenis, V. (2012). Using the UKCP09 probabilistic scenarios to model the amplified impact of climate change on drainage basin sediment yield. *Hydrol. Earth Syst. Sci.,* 16(11), 4401-4416. https://doi.org/10.5194/hess-16-4401-2012

Precipitation intensities and the frequency of extreme events are projected to increase under climate change. These rainfall changes will lead to increases in the magnitude and frequency of flood events that will, in turn, affect patterns of erosion and deposition within river basins. These geomorphic changes to river systems may affect flood conveyance, infrastructure resilience, channel pattern, and habitat status as well as sediment, nutrient and carbon fluxes. Previous research modelling climatic influences on geomorphic changes has been limited by how climate variability and change are represented by downscaling from global or regional climate models. Furthermore, the non-linearity of

the climatic, hydrological and geomorphic systems involved generate large uncertainties at each stage of the modelling process creating an uncertainty "cascade".
This study integrates state-of-the-art approaches from the climate change and geomorphic communities to address these issues in a probabilistic modelling study of the Swale catchment, UK. The UKCP09 weather generator is used to simulate hourly rainfall for the baseline and climate change scenarios up to 2099, and used to drive the CAESAR landscape evolution model to simulate geomorphic change. Results show that winter rainfall is projected to increase, with larger increases at the extremes. The impact of the increasing rainfall is amplified through the translation into catchment runoff and in turn sediment yield with a 100% increase in catchment mean sediment yield predicted between the baseline and the 2070–2099 High emissions scenario. Significant increases are shown between all climate change scenarios and baseline values. Analysis of extreme events also shows the amplification effect from rainfall to sediment delivery with even greater amplification associated with higher return period events. Furthermore, for the 2070–2099 High emissions scenario, sediment discharges from 50-yr return period events are predicted to be 5 times larger than baseline values.

Culley, S., Noble, S., Yates, A., Timbs, M., Westra, S., Maier, H. R., . . . Castelletti, A. (2016). A bottom-up approach to identifying the maximum operational adaptive capacity of water resource systems to a changing climate. *Water Resources Research,* 52(9), 6751-6768. https://doi.org/10.1002/2015wr018253

Many water resource systems have been designed assuming that the statistical characteristics of future inflows are similar to those of the historical record. This assumption is no longer valid due to large-scale changes in the global climate, potentially causing declines in water resource system performance, or even complete system failure. Upgrading system infrastructure to cope with climate change can require substantial financial outlay, so it might be preferable to optimize existing system performance when possible. This paper builds on decision scaling theory by proposing a bottom-up approach to designing optimal feedback control policies for a water system exposed to a changing climate. This approach not only describes optimal operational policies for a range of potential climatic changes but also enables an assessment of a system's upper limit of its operational adaptive capacity, beyond which upgrades to infrastructure become unavoidable. The approach is illustrated using the Lake Como system in Northern Italya regulated system with a complex relationship between climate and system performance. By optimizing system operation under different hydrometeorological states, it is shown that the system can continue to meet its minimum performance requirements for more than three times as many states as it can under current operations. Importantly, a single management policy, no matter how robust, cannot fully utilize existing infrastructure as effectively as an ensemble of flexible management policies that are updated as the climate changes.

DeCristofaro, L., & Palmer, R. N. (2015). *Evaluating the performance of multiple alternative operating rules under climate change: A case study of New York City*. https://doi.org/10.1061/9780784479162.210

An increase in climate variability due to increased greenhouse gases in the Earth's atmosphere poses challenges for water management. Current operating rules for the New York City Water Supply System (NYCWSS) are designed to manage water levels and mitigate the effects of extreme precipitation on the quality of water provided to the end user. Questions remain as to whether these rules will continue to be robust under future climates. A screening tool simulating the operations of the NYCWSS is developed, which couples with a hydrology model developed in part with the New York City Department of Environmental Protection (NYCDEP). To observe operating rules and alternatives under varying climate, this study used a stochastic weather generator to create a number of long time-series to test the system. Parameters used in the weather generator were incrementally varied. In all cases, the change incurred by a changing climate is larger than the change effected by small operational changes, though overall reliability is not threatened. These preliminary screening results will allow NYCDEP to focus on the rule changes and climate futures of greatest interest to them.

Dessai, S., & Hulme, M. (2007). Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England. *Global Environmental Change-Human and Policy Dimensions,* 17(1), 59-72. https://doi.org/10.1016/j.gloenvcha.2006.11.005

Projections of future climate change are plagued with uncertainties, causing difficulties for planners taking decisions on adaptation measures. This paper presents an assessment framework that allows the identification of adaptation strategies that are robust (i.e. insensitive) to climate change uncertainties. The framework is applied to a case study of water resources management in the East of England, more specifically to the Anglian Water Services' 25 year Water Resource Plan (WRP). The paper presents a local sensitivity analysis (a 'one-at-a-time' experiment) of the various elements of the modelling framework (e.g., emissions of greenhouse gases, climate sensitivity and global climate models) in order to determine whether or not a decision to adapt to climate change is sensitive to uncertainty in those elements. Water resources are found to be sensitive to uncertainties in regional climate response (from general circulation models and dynamical downscaling), in climate sensitivity and in climate impacts. Aerosol forcing and greenhouse gas emissions uncertainties are also important, whereas uncertainties from ocean mixing and the carbon cycle are not. Despite these large uncertainties, Anglian Water Services' WRP remains robust to the climate change uncertainties sampled because of the adaptation options being considered (e.g. extension of water treatment works), because the climate model used for their planning (HadCM3) predicts drier conditions than other models, and because 'one-at-a-time' experiments do not sample the combination of different extremes in the uncertainty range of parameters. This research raises the question of how much certainty is required in climate change projections to justify investment in adaptation measures, and whether such certainty can be delivered.

Dhillon, D., Pingel, N., Lee, D., & Horvath, M. (2017). *Assessing Flood Risk over Time Using Expected Annual Damage Information from the 2017 Central Valley Flood Protection Plan Update*. https://doi.org/10.1061/9780784480601.055

California has already taken actions to reduce flood risk in the Central Valley through investments in the flood management infrastructure and emergency response systems. However, California's growing population will increase vulnerability and exposure to the flood hazard. Further, a changing climate may expand areas subject to inundation. Lastly, the flood control system that protects Californians in the Central Valley is aging and enhancements are needed. This study tracked the State's investments and associated flood risk reduction benefits from the recent past to the future, through the planning horizon of the 2017 Central Valley Flood Protection Plan (CVFPP) Update. Here, we discuss how flood risk is assessed over time. We use two indicators of flood risk: expected annual damage (EAD) and expected annual fatalities (i.e., life loss). Both are used to measure the benefit of the investment thus far, and to measure the benefit of future investments in light of changing conditions such as population growth and climate change. We describe inputs to the EAD and life loss computations and how EAD and life loss is computed using HEC-FDA, the standard-of-practice of software developed by the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center. HEC-FDA performs integrated hydrologic engineering and economic analysis. We also describe how inputs to EAD and life loss computations are likely to change over time both with and without the activities included in the 2017 CVFPP Update.

Dittmer, K. (2013). Changing streamflow on Columbia basin tribal lands-climate change and salmon. *Climatic Change,* 120(3), 627-641. https://doi.org/10.1007/s10584-013-0745-0

Over the last 100 years, linear trends of tributary streamflow have changed on Columbia River Basin tribal reservations and historical lands ceded by tribes in treaties with the United States. Analysis of independent flow measures (Seasonal Flow Fraction, Center Timing, Spring Flow Onset, High Flow, Low Flow) using the Student t test and Mann-Kendall trend test suggests evidence for climate change trends for many of the 32 study basins. The trends exist despite interannual climate variability driven by the El Nio-Southern Oscillation and Pacific Decadal Oscillation. The average April-July flow volume declined by 16 %. The median runoff volume date has moved earlier by 5.8 days. The Spring Flow Onset date has shifted earlier by 5.7 days. The trend of the flow standard deviation (i.e., weather variability) increased 3 % to 11 %. The 100-year November floods increased 49 %. The mid-Columbia 7Q10 low flows have decreased by 5 % to 38 %. Continuation of these climatic and hydrological trends may seriously challenge the future of salmon, their critical habitats, and the tribal peoples who depend upon these resources for their traditional livelihood, subsistence, and ceremonial purposes.

Donley, E. E., Naiman, R. J., & Marineau, M. D. (2012). Strategic planning for instream flow restoration: a case study of potential climate change impacts in the central Columbia River basin. *Global Change Biology,* 18(10), 3071-3086. https://doi.org/10.1111/j.1365-2486.2012.02773.x

We provide a case study prioritizing instream flow restoration activities by sub-basin according to the habitat needs of Endangered Species Act (ESA)-listed salmonids relative to climate change in the central Columbia River basin in Washington State (USA). The objective is to employ scenario analysis to inform and improve existing instream flow restoration projects. We assess the sensitivity of late summer (July, August, and September) flows to the following scenario simulations singly or in combination: climate change, changes in the quantity of water used for irrigation and possible changes to existing water resource policy. Flows for four sub-basins were modeled using the Water Evaluation and Planning system (WEAP) under historical and projected conditions of 2020 and 2040 for each scenario. Results indicate that Yakima will be the most flow-limited sub-basin with average reductions in streamflow of 41% under climate conditions of 2020 and 56% under 2040 conditions; 1.32.5 times greater than those of other sub-basins. In addition, irrigation plays a key role in the hydrology of the Yakima sub-basin with flow reductions ranging from 78% to 90% under severe to extreme (i.e., 2040%) increases in agricultural water use (2.04.4 times the reductions in the other sub-basins). The Yakima and Okanogan sub-basins are the most responsive to simulations of flow-bolstering policy change (providing salmon with first priority water allocation and at biologically relevant flows), as demonstrated by 91100% target flows attained. The Wenatchee and Methow sub-basins do not exhibit similar responsiveness to simulated policy changes. Considering climate change only, we conclude that flow restoration should be prioritized first in the Yakima and Wenatchee sub-basins, and second in the Okanogan and Methow. Considering both climate change and possible policy changes, we recommend that the Yakima sub-basin receive the highest priority for flow restoration activities to sustain critical instream habitat for ESA-listed salmonids.

Dudley, P. N. (2018). A salmonid individual-based model as a proposed decision support tool for management of a large regulated river. *Ecosphere,* 9(1). https://doi.org/10.1002/ecs2.2074

Large regulated rivers often require fisheries and water managers to make management decisions involving resident fish population dynamics that have many ecological drivers. Because of the large scale of the system and often competing interests and demands for water, there is a critical need for decision support tools (DSTs) that allow examination of alternative management scenarios while considering key ecological interactions. Spatially explicit individual-based models (IBMs) can serve as effective DSTs by providing information on fish population dynamics while accounting for, and providing extensive, spatially explicit information on, the numerous ecological drivers. Spatially explicit IBMs are often difficult to implement owing to the numerous and often complex inputs the models require. Here, I demonstrate how a suite of free, graphical user interface equipped programs, along with three custom-built and publicly available plugins, can streamline the modeling process and serve as a IBM-based DST for fisheries management on large regulated rivers. The main program is a spatially explicit IBM of juvenile salmonid dynamics, inSALMO, with two other programs that generate the key input data in the required spatially explicit formats. I then use this proposed DST to simulate a Chinook salmon population on a portion of California's Sacramento River to determine whether an IBM-based DST is appropriate to evaluate management impacts on a large regulated river. The Sacramento is a large river of major concern in California and is representative of many rivers in the United States and worldwide in that it is dammed, has a resident fish population, and is heavily used for water supply. The proposed DTS results compare favorably with the predictive power of a general additive model, while providing a much fuller and richer data set that could significantly aid and inform management decisions.

Dunmall, K. M., Mochnacz, N. J., Zimmerman, C. E., Lean, C., & Reist, J. D. (2016). Using thermal limits to assess establishment of fish dispersing to high-latitude and high-elevation watersheds. *Canadian Journal of Fisheries and Aquatic Sciences,* 73(12), 1750-1758. https://doi.org/10.1139/cjfas-2016-0051

Distributional shifts of biota to higher latitudes and elevations are presumably influenced by species-specific physiological tolerances related to warming temperatures. However, it is establishment rather than dispersal that may be limiting colonizations in these cold frontier areas. In freshwater ecosystems, perennial groundwater springs provide critical winter thermal refugia in these extreme environments. By reconciling the thermal characteristics of these refugia with the minimum thermal tolerances of life stages critical for establishment, we develop a strategy to focus broad projections of northward and upward range shifts to the specific habitats that are likely for establishments. We evaluate this strategy using chum salmon (Oncorhynchus keta) and pink salmon (Oncorhynchus gorbuscha) that seem poised to colonize Arctic watersheds. Stream habitats with a minimum temperature of 4 degrees C during spawning and temperatures above 2 degrees C during egg incubation were most vulnerable to establishments by chum and pink salmon. This strategy will improve modelling forecasts of range shifts for cold freshwater habitats and focus proactive efforts to conserve both newly emerging fisheries and native species at northern and upper distributional extremes.

East, A. E., & Sankey, J. B. (2020). Geomorphic and Sedimentary Effects of Modern Climate Change: Current and Anticipated Future Conditions in the Western United States. *Reviews of Geophysics,* 58(4). https://doi.org/10.1029/2019rg000692

Hydroclimatic changes associated with global warming over the past 50 years have been documented widely, but physical landscape responses are poorly understood thus far. Detecting sedimentary and geomorphic signals of modern climate change presents challenges owing to short record lengths, difficulty resolving signals in stochastic natural systems, influences of land use and tectonic activity, long-lasting effects of individual extreme events, and variable connectivity in sediment-routing systems. We review existing literature to investigate the nature and extent of sedimentary and geomorphic responses to modern climate change, focusing on the western United States, a region with generally high relief and high sediment yield likely to be sensitive to climatic forcing. Based on fundamental geomorphic theory and empirical evidence from other regions, we anticipate climate-driven changes to slope stability, watershed sediment yields, fluvial morphology, and aeolian sediment mobilization in the western United States. We find evidence for recent climate-driven changes to slope stability and increased aeolian dune and dust activity, whereas changes in sediment yields and fluvial morphology have been linked more commonly to nonclimatic drivers thus far. Detecting effects of climate change will require better understanding how landscape response scales with disturbance, how lag times and hysteresis operate within sedimentary systems, and how to distinguish the relative influence and feedbacks of superimposed disturbances. The ability to constrain geomorphic and sedimentary response to rapidly progressing climate change has widespread implications for human health and safety, infrastructure, water security, economics, and ecosystem resilience.

Economic Commission for Europe, & International Network of Basin Organizations. (2015). *Water and Climate Change Adaptation in Transboundary Basins: Lessons Learned and Good Practices.* Retrieved from https://unece.org/fileadmin/DAM/env/water/publications/WAT_Good_practices/ece.mp.wat.45.pdf

Climate change impacts are both episodic, such as extreme weather events, and long-term and permanent, for example, due to changes in flow regimes and absolute water balances. To address uncertainties that exist about the direction, speed and intensity of climate change, water resources policy and management should include practices that ensure that water usage is ecologically sensitive, are consistent with sustainable development and are robust across a wide range of climate futures. Because of the complexity of climate change impacts on the water cycle and how these impacts can be expressed in one part of a basin but felt in other, far distant parts of the same basin, effective adaptation to climate change requires coordination, integration and coherence across political, sectoral, ecological and institutional boundaries.
Authorities in some water basins — particularly the 14 members of the ECE/INBO global network of basins working on climate change adaptation — have already started the planning and development of activities related to adaptation to climate change. It is crucial to benefit from their experiences by identifying and collecting the good practices from around the world and by sharing those good practices and lessons learned — the aim of this publication.

Eum, H. I., Sredojevic, D., & Simonovic, S. P. (2011). Engineering Procedure for the Climate Change Flood Risk Assessment in the Upper Thames River Basin. *Journal of Hydrologic Engineering,* 16(7), 608-612. https://doi.org/10.1061/(asce)he.1943-5584.0000346

Climate change will bring more severe and frequent floods to the Upper Thames River basin. The city of London, with a population of over 350,000, is one of the most vulnerable locations in the basin. This paper presents an original methodology used to prepare the input for flood risk assessment under climate change. The methodology involves integrated climate-hydrologic-hydraulic modeling analyses for floodplain mapping under the changing climatic conditions. Using 43 years of historical data at 15 stations in the Upper Thames River basin and global circulation model predictions, the potential climate change impacts on flood risk in the basin are provided. The results indicate that, under climate change, the extent of flood impacts will be larger (larger areas inundated with larger water depth), and will therefore increase the level of risk to public infrastructure. Results of the study are being used in a quantitative assessment of risk to the municipal infrastructure.

Fan, R., Tong, S. T. Y., & Lee, J. G. (2017). Determining the Optimal BMP Arrangement under Current and Future Climate Regimes: Case Study. *Journal of Water Resources Planning and Management,* 143(9). https://doi.org/10.1061/(asce)wr.1943-5452.0000816

As watersheds are urbanized, the amount of impervious surfaces will be increased. As such, water infiltration will be reduced, and the volume of surface runoff will be increased. By retaining stormwater, best management practices (BMPs) are used to mitigate the hydrologic effects of urbanization. Using the Ludlow watershed in northern Kentucky as a case study, the main objective of this paper was to identify the most cost-effective arrangement of BMPs in reducing surface runoff. A simulation program was employed to model the hydrologic conditions in the Ludlow watershed under the current and future climate conditions and to identify the most cost-effective BMP arrangement. The results show that the simulation program is an effective tool in simulating a small watershed. Indeed, BMPs are instrumental in reducing surface runoff even when the future climate becomes drier. The most cost-effective BMP arrangement is to install two infiltration trenches and one bioretention in the watershed. These findings can be useful in watershed management in areas with similar hydroclimatic conditions.

Fankhauser, S., Smith, J. B., & Tol, R. S. J. (1999). Weathering climate change: some simple rules to guide adaptation decisions. *Ecological Economics,* 30(1), 67-78. https://doi.org/10.1016/s0921-8009(98)00117-7

This paper discusses some of the elements that may characterise an efficient strategy to adapt to a changing climate. Such a strategy will have to reflect the long time horizon of, and the prevailing uncertainties about, climate change. An intuitively appealing approach therefore seems to be to enhance the flexibility and resilience of systems to react to and cope with climate shocks and extremes, as well as to improve information. In addition, in the case of quasi-irreversible investments with a long lifetime (e.g. infrastructure investments, development of coastal zones) precautionary adjustments may be called for to increase the robustness of structures, or to increase the rate of depreciation to allow for earlier replacement. Many of these measures may already have to be considered now, and could be worthwhile in their own right, independent of climate change considerations.

Fatichi, S., Rimkus, S., Burlando, P., & Bordoy, R. (2014). Does internal climate variability overwhelm climate change signals in streamflow? The upper Po and Rhone basin case studies. *Science of the Total Environment,* 493, 1171-1182. https://doi.org/10.1016/j.scitotenv.2013.12.014

Projections of climate change effects in streamflow are increasingly required to plan water management strategies. These projections are however largely uncertain due to the spread among climate model realizations, internal climate variability, and difficulties in transferring climate model results at the spatial and temporal scales required by catchment hydrology. A combination of a stochastic downscaling methodology and distributed hydrological modeling was used in the ACQWA project to provide projections of future streamflow (up to year 2050) for the upper Po and Rhone basins, respectively located in northern Italy and south-western Switzerland. Results suggest that internal (stochastic) climate variability is a fundamental source of uncertainty, typically comparable or larger than the projected climate change signal. Therefore, climate change effects in streamflow mean, frequency, and seasonality can be masked by natural climatic fluctuations in large parts of the analyzed regions. An exception to the overwhelming role of stochastic variability is represented by high elevation catchments fed by glaciers where streamflow is expected to be considerably reduced due to glacier retreat, with consequences appreciable in the main downstream rivers in August and September. Simulations also identify regions (west upper Rhone and Toce, Ticino river basins) where a strong precipitation increase in the February to April period projects streamflow beyond the range of natural climate variability during the melting season. This study emphasizes the importance of including internal climate variability in climate change analyses, especially when compared to the limited uncertainty that would be accounted for by few deterministic projections. The presented results could be useful in guiding more specific impact studies, although design or management decisions should be better based on reliability and vulnerability criteria as suggested by recent literature.

Ficklin, D. L., Abatzoglou, J. T., Robeson, S. M., Null, S. E., & Knouft, J. H. (2018). Natural and managed watersheds show similar responses to recent climate change. *Proceedings of the National Academy of Sciences of the United States of America,* 115(34), 8553-8557. https://doi.org/10.1073/pnas.1801026115

Changes in climate are driving an intensification of the hydrologic cycle and leading to alterations of natural streamflow regimes. Human disturbances such as dams, land-cover change, and water diversions are thought to obscure climate signals in hydrologic systems. As a result, most studies of changing hydroclimatic conditions are limited to areas with natural streamflow. Here, we compare trends in observed streamflow from natural and human-modified watersheds in the United States and Canada for the 1981-2015 water years to evaluate whether comparable responses to climate change are present in both systems. We find that patterns and magnitudes of trends in median daily streamflow, daily streamflow variability, and daily extremes in human-modified watersheds are similar to those from nearby natural watersheds. Streamflow in both systems show negative trends throughout the southern and western United States and positive trends throughout the northeastern United States, the northern Great Plains, and southern prairies of Canada. The trends in both natural and human-modified watersheds are linked to local trends in precipitation and reference evapotranspiration, demonstrating that water management and land-cover change have not substantially altered the effects of climate change on human-modified watersheds compared with nearby natural watersheds.

Forsee, W. J., & Ahmad, S. (2011). Evaluating Urban Storm-Water Infrastructure Design in Response to Projected Climate Change. *Journal of Hydrologic Engineering,* 16(11), 865-873. https://doi.org/10.1061/(asce)he.1943-5584.0000383

One of the goals of storm-water infrastructure design is to mitigate effects resulting from extreme hydrologic events. Projected changes in climate are expected to lead to an increase in the frequency and magnitude of extreme rainfall events for many regions. Accordingly, existing storm-water infrastructure may not meet design standards in future decades. The North American Regional Climate Change Assessment Program is currently disseminating high resolution climate data to facilitate climate change impact assessments. A simple framework is presented for assessment of storm-water infrastructure in response to climate change. First, the projected changes in the 6-hour, 100-year design-storm depth for a watershed in Las Vegas Valley, Nevada, are calculated from several climate scenarios by using regional frequency analysis. Climate model projections vary substantially for this region and time scale. Climate model performance is assessed by using gridded reanalysis data. The projected changes in design-storm depths are incorporated into an existing HEC-HMS model. The HEC-HMS simulation results indicate potential exceedences of current design standards for select storm-water infrastructure components under projected climatic change scenarios.

Frei, C. M., Hotchkiss, R. H., & Bergendahl, B. (2005). Design for Fish Passage for Bridges and Culverts. In *Impacts of Global Climate Change.* (pp. 1-10) https://doi.org/10.1061/40792(173)403

The Federal Highways Administration and Washington State University are collaborating to produce Hydraulic Engineering Circular 26: "Design of Fish Passage for Bridges and Culverts"; a comprehensive manual for the design or retrofit of a stream crossing to meet fish passage requirements. Input from State Departments of Transportation, non-governmental organizations, and other interested parties will be combined with new research and an extensive literature review to compile design methods, culvert and stream assessment techniques, case studies, and design examples. The manual will provide a set of guidelines to any party interested in the design or retrofit of culverts and bridges to meet fish passage requirements, and is intended to streamline the design process.

Fullerton, A. H., Torgersen, C. E., Lawler, J. J., Steel, E. A., Ebersole, J. L., & Lee, S. Y. (2018). Longitudinal thermal heterogeneity in rivers and refugia for coldwater species: effects of scale and climate change. *Aquatic Sciences,* 80(1). https://doi.org/10.1007/s00027-017-0557-9

Climate-change driven increases in water temperature pose challenges for aquatic organisms. Predictions of impacts typically do not account for fine-grained spatiotemporal thermal patterns in rivers. Patches of cooler water could serve as refuges for anadromous species like salmon that migrate during summer. We used high-resolution remotely sensed water temperature data to characterize summer thermal heterogeneity patterns for 11,308 km of second-seventh-order rivers throughout the Pacific Northwest and northern California (USA). We evaluated (1) water temperature patterns at different spatial resolutions, (2) the frequency, size, and spacing of cool thermal patches suitable for Pacific salmon (i.e., contiguous stretches >= 0.25 km, <= 15 degrees C and >= 2 degrees C, aooler than adjacent water), and (3) potential influences of climate change on availability of cool patches. Thermal heterogeneity was nonlinearly related to the spatial resolution of water temperature data, and heterogeneity at fine resolution (<1 km) would have been difficult to quantify without spatially continuous data. Cool patches were generally >2.7 and <13.0 km long, and spacing among patches was generally >5.7 and <49.4 km. Thermal heterogeneity varied among rivers, some of which had long uninterrupted stretches of warm water >= 20 degrees C, and others had many smaller cool patches. Our models predicted little change in future thermal heterogeneity among rivers, but within-river patterns sometimes changed markedly compared to contemporary patterns. These results can inform long-term monitoring programs as well as near-term climate-adaptation strategies.

Gillespie, N., Unthank, A., Campbell, L., Anderson, P., Gubernick, R., Weinhold, M., . . . Kirn, R. (2014). Flood Effects on Road–Stream Crossing Infrastructure: Economic and Ecological Benefits of Stream Simulation Designs. *Fisheries,* 39(2), 62-76. https://doi.org/10.1080/03632415.2013.874527

Stream simulation design is a geomorphic, engineering, and ecologically based approach to designing road-stream crossings that creates a natural and dynamic channel through the crossing structure similar in dimensions and characteristics to the adjacent natural channel, allowing for unimpeded passage of aquatic organisms, debris, and water during various flow conditions, including floods. A retrospective case study of the survival and failure of road-stream crossings was conducted in the upper White River watershed and the Green Mountain National Forest in Vermont following record flooding from Tropical Storm Irene in August 2011. Damage was largely avoided at two road-stream crossings where stream simulation design was implemented and extensive at multiple road-stream crossings constructed using traditional undersized hydraulic designs. Cost analyses suggest that relatively modest increases in initial investment to implement stream simulation designs yield substantial societal and economic benefits. Recommendations are presented to help agencies and stakeholders improve road-stream crossings, including increasing coordination to adopt stream simulation design methodology, increasing funding and flexibility for agencies and partners to upgrade failed crossings for flood resiliency, and expanding training workshops targeting federal, state, and local stakeholders.

Goode, J. R., Buffington, J. M., Tonina, D., Isaak, D. J., Thurow, R. F., Wenger, S., . . . Soulsby, C. (2013). Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. *Hydrological Processes,* 27(5), 750-765. https://doi.org/10.1002/hyp.9728

Snowmelt-dominated basins in northern latitudes provide critical habitat for salmonids. As such, these systems may be especially vulnerable to climate change because of potential shifts in the frequency, magnitude, and timing of flows that can scour incubating embryos. A general framework is presented to examine this issue, using a series of physical models that link climate change, streamflow, and channel morphology to predict the magnitude and spatial distribution of streambed scour and consequent risk to salmonid embryos at basin scales. The approach is demonstrated for a mountain catchment in the Northern Rocky Mountains, USA. Results show that risk of critical scour varies as a function of species and life history and is modulated by local variations in lithology and channel confinement. Embryos of smaller-bodied fall spawners may be at greater risk because of shallow egg burial depths and increased rain-on-snow events during their incubation period. Scour risk for all species is reduced when changes in channel morphology (width, depth, and grain size) keep pace with climate-driven changes in streamflow. Although climate change is predicted to increase scour magnitude, the frequency of scouring events relative to typical salmonid life cycles is relatively low, indicating that individual year classes may be impacted by critical scour, but extirpation of entire populations is not expected. Furthermore, refugia are predicted to occur in unconfined portions of the stream network, where scouring shear stresses are limited to bankfull stage because overbank flows spread across alluvial floodplains; conversely, confined valleys will likely exacerbate climate-driven changes in flow and scour. Our approach can be used to prioritize management strategies according to relative risk to different species or spatial distributions of risk and can be used to predict temporal shifts in the spatial distribution of suitable spawning habitats. A critical unknown issue is whether biological adaptation can keep pace with rates of climate change and channel response.

Graves, D., & Chang, H. (2007). Hydrologic Impacts of Climate Change in the Upper Clackamas River Basin, Oregon, USA. *Climate Research,* 33, 143-157. https://doi.org/10.3354/cr033143

The Pacific Northwest of the USA is dependent on seasonal snowmelt for water resources that support its economy and aquatic ecosystems. Increased temperatures resulting from higher concentrations of atmospheric greenhouse gases may cause disruptions to these resources because of reductions in the annual snowpack and the earlier occurrence of seasonal snowmelt. We applied a Geographic Information System (GIS)-based distributed hydrologic model at a monthly scale to assess the effects of future climate change on runoff from the Upper Clackamas River Basin (UCB; located near Portland, Oregon, USA). Once validated using historic flow data, the model was run for 2 future time periods (2010–2039 and 2070–2099) using climate change simulations from 2 global circulation modelling groups (HadCM2 from the Hadley Centre for Climate Prediction and Research, and CGCM1 from the Canadian Centre for Climate Modelling and Analysis) as inputs. The model runs projected that mean peak snowpack in the study area will drop dramatically (36 to 49% by 2010–2039, and 83 to 88% by 2070–2099), resulting in earlier runoff and diminished spring and summer flows. Increases in mean winter runoff by 2070–2099 vary from moderate (13.7%) to large (46.4%), depending on the changes to precipitation projected by the general circulation models (GCMs). These results are similar to those of other studies in areas dependent on snowpack for seasonal runoff, but the reductions to snowpack are more severe in this study than in similar studies of the entire Columbia River Basin, presumably because the elevations of much of the Upper Clackamas Basin are near the current mid-winter snow line.

Groves, D. G., Yates, D., & Tebaldi, C. (2008). Developing and applying uncertain global climate change projections for regional water management planning. *Water Resources Research,* 44(12). https://doi.org/10.1029/2008wr006964

Climate change may impact water resources management conditions in difficult-to-predict ways. A key challenge for water managers is how to incorporate highly uncertain information about potential climate change from global models into local- and regional-scale water management models and tools to support local planning. This paper presents a new method for developing large ensembles of local daily weather that reflect a wide range of plausible future climate change scenarios while preserving many statistical properties of local historical weather patterns. This method is demonstrated by evaluating the possible impact of climate change on the Inland Empire Utilities Agency service area in southern California. The analysis shows that climate change could impact the region, increasing outdoor water demand by up to 10% by 2040, decreasing local water supply by up to 40% by 2040, and decreasing sustainable groundwater yields by up to 15% by 2040. The range of plausible climate projections suggests the need for the region to augment its long-range water management plans to reduce its vulnerability to climate change.

Hamlet, A. F. (2011). Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America. *Hydrology and Earth System Sciences,* 15(5), 1427-1443. https://doi.org/10.5194/hess-15-1427-2011

Climate change impacts in Pacific Northwest Region of North America (PNW) are projected to include increasing temperatures and changes in the seasonality of precipitation (increasing precipitation in winter, decreasing precipitation in summer). Changes in precipitation are also spatially varying, with the northwestern parts of the region generally experiencing greater increases in cool season precipitation than the southeastern parts. These changes in climate are projected to cause loss of snowpack and associated streamflow timing shifts which will increase cool season (October-March) flows and decrease warm season (April-September) flows and water availability. Hydrologic extremes such as the 100 yr flood and extreme low flows are also expected to change, although these impacts are not spatially homogeneous and vary with mid-winter temperatures and other factors. These changes have important implications for natural ecosystems affected by water, and for human systems. The PNW is endowed with extensive water resources infrastructure and well-established and well-funded management agencies responsible for ensuring that water resources objectives (such as water supply, water quality, flood control, hydropower production, environmental services, etc.) are met. Likewise, access to observed hydrological, meteorological, and climatic data and forecasts is in general exceptionally good in the United States and Canada, and is often supported by federally funded programs that ensure that these resources are freely available to water resources practitioners, policy makers, and the general public. Access to these extensive resources support the argument that at a technical level the PNW has high capacity to deal with the potential impacts of natural climate variability on water resources. To the extent that climate change will manifest itself as moderate changes in variability or extremes, we argue that existing water resources infrastructure and institutional arrangements provide a reasonably solid foundation for coping with climate change impacts, and that the mandates of existing water resources policy and water resources management institutions are at least consistent with the fundamental objectives of climate change adaptation. A deeper inquiry into the underlying nature of PNW water resources systems, however, reveals significant and persistent obstacles to climate change adaptation, which will need to be overcome if effective use of the region's extensive water resources management capacity can be brought to bear on this problem. Primary obstacles include assumptions of stationarity as the fundamental basis of water resources system design, entrenched use of historical records as the sole basis for planning, problems related to the relatively short time scale of planning, lack of familiarity with climate science and models, downscaling procedures, and hydrologic models, limited access to climate change scenarios and hydrologic products for specific water systems, and rigid water allocation and water resources operating rules that effectively block adaptive response. Institutional barriers include systematic loss of technical capacity in many water resources agencies following the dam building era, jurisdictional fragmentation affecting response to drought, disconnections between water policy and practice, and entrenched bureaucratic resistance to change in many water management agencies. These factors, combined with a federal agenda to block climate change policy in the US during the Bush administration have (with some exceptions) contributed to widespread institutional "gridlock" in the PNW over the last decade or so despite a growing awareness of climate change as a significant threat to water management. In the last several years, however, significant progress has been made in surmounting some of these obstacles, and the region's water resources agencies at all levels of governance are making progress in addressing the fundamental challenges inherent in adapting to climate change.

Hamlet, A. F., Elsner, M. M., Mauger, G. S., Lee, S. Y., Tohver, I., & Norheim, R. A. (2013). An Overview of the Columbia Basin Climate Change Scenarios Project: Approach, Methods, and Summary of Key Results. *Atmosphere-Ocean,* 51(4), 392-415. https://doi.org/10.1080/07055900.2013.819555

The Columbia Basin Climate Change Scenarios Project (CBCCSP) was conceived as a comprehensive hydrologic database to support climate change planning, impacts assessment, and adaptation in the Pacific Northwest (PNW) by a diverse user community with varying technical capacity over a wide range of spatial scales. The study has constructed a state-of-the-art, end-to-end data processing sequence from "raw" climate model output to a suite of hydrologic modelling products that are served to the user community from a web-accessible database. A calibrated 1/16 degree latitude-longitude resolution implementation of the VIC hydrologic model over the Columbia River basin was used to produce historical simulations and 77 future hydrologic projections associated with three different statistical downscaling methods and three future time periods (2020s, 2040s, and 2080s). Key products from the study include summary data for about 300 river locations in the PNW and monthly Geographic Information System products for 21 hydrologic variables over the entire study domain. Results from the study show profound changes in spring snowpack and fundamental shifts from snow and mixed-rain-and-snow to rain-dominant behaviour across most of the domain. Associated shifts in streamflow timing from spring and summer to winter are also evident in basins with significant snow accumulation in winter (for the current climate). Potential evapotranspiration increases over most of the PNW in summer because of rising temperatures; however, actual evapotranspiration is reduced in all but a few areas of the domain because evapotranspiration is mostly water limited in summer, and summer precipitation decreases in the simulations. Simulated widespread increases in soil moisture recharge in fall and winter in areas with significant snow accumulation in winter (for the current climate) support hypotheses of increased landslide risk and sediment transport in winter in the future. Simulations of floods and extreme low flows increase in intensity for most of the river sites included in the study. The largest increases in flooding are in mixed-rain-and-snow basins whose current mid-winter temperatures are within a few degrees of freezing. The CBCCSP database has been a valuable public resource that has dramatically reduced costs in a number of high-visibility studies in the PNW and western United States focused on technical coordination and planning.

Hamlet, A. F., Mauger, G. S., Lee, S. Y., Won, J., & Byun, K. (2018). *New Risk-Based Decision Support Tools for Designing Culverts for Fish Passage in a Changing Climate.* Paper presented at the American Geophysical Union, Fall Meeting. Retrieved from https://ui.adsabs.harvard.edu/abs/2018AGUFMPA33F1206H/abstract

As part of a long-term collaboration to improve culvert design in a changing climate in the Pacific Northwest region, this project extends methods recently developed by the Washington State Dept. of Fish and Wildlife (WDFW) for designing culverts for fish passage under climate change. Specifically, based on analytical approaches recently developed at the University of Notre Dame (UND), researchers at the U. of Washington Climate Impacts Group, Skagit Climate Science Consortium, and the UND have developed an on-line prototype for a new design tool that estimates the probability that a proposed culvert design will fail to provide appropriate fish passage during its design lifespan. The tool works by estimating a required culvert size for fish passage for each future year in a culvert's design life using streamflow projections from an ensemble of ten CMIP3 climate change scenarios. Uncertainties in the future culvert size requirements are bootstrapped via Monte Carlo techniques, and a 95% confidence bound is established. If the required culvert size for a particular ensemble member and future design year exceeds a proposed design width with 95% confidence, then the scenario is counted as a fish passage "failure" for that climate ensemble member and future year. Finally, the number of scenarios that produce a fish passage failure are tallied for all ensemble members and future years to estimate the overall probability that a design failure will occur over the design lifespan. Users of the on-line tool select a location for the proposed culvert, a design lifespan, and a proposed culvert design width, and the tool calculates the probability of fish passage failure over the design lifespan. The tool can easily be adapted to incorporate alternate design criteria for culvert sizing, and also different levels of risk tolerance in the management community. In future work, the authors plan to work with WDFW and other research partners to refine the new tool and incorporate these new approaches in the official culvert design process used by WDFW for WA.

Herman, J. D., Quinn, J. D., Steinschneider, S., Giuliani, M., & Fletcher, S. (2020). Climate Adaptation as a Control Problem: Review and Perspectives on Dynamic Water Resources Planning Under Uncertainty. *Water Resources Research,* 56(2). https://doi.org/10.1029/2019wr025502

Climate change introduces substantial uncertainty to water resources planning and raises the key question: when, or under what conditions, should adaptation occur? A number of recent studies aim to identify policies mapping future observations to actions-in other words, framing climate adaptation as an optimal control problem. This paper uses the control paradigm to review and classify recent dynamic planning studies according to their approaches to uncertainty characterization, policy structure, and solution methods. We propose a set of research gaps and opportunities in this area centered on the challenge of characterizing uncertainty, which prevents the unambiguous application of control methods to this problem. These include exogenous uncertainty in forcing, model structure, and parameters propagated through a chain of climate and hydrologic models; endogenous uncertainty in human-environmental system dynamics across multiple scales; and sampling uncertainty due to the finite length of historical observations and future projections. Recognizing these challenges, several opportunities exist to improve the use of control methods for climate adaptation, namely, how problem context and understanding of climate processes might assist with uncertainty quantification and experimental design, out-of-sample validation and robustness of optimized adaptation policies, and monitoring and data assimilation, including trend detection, Bayesian inference, and indicator variable selection. We conclude with a summary of recommendations for dynamic water resources planning under climate change through the lens of optimal control.

Herman, J. D., Reed, P. M., Zeff, H. B., & Characklis, G. W. (2015). How Should Robustness Be Defined for Water Systems Planning under Change? *Journal of Water Resources Planning and Management,* 141(10). https://doi.org/10.1061/(asce)wr.1943-5452.0000509

Water systems planners have long recognized the need for robust solutions capable of withstanding deviations from the conditions for which they were designed. Robustness analyses have shifted from expected utility to exploratory bottom-up approaches which identify vulnerable scenarios prior to assigning likelihoods. Examples include Robust Decision Making (RDM), Decision Scaling, Info-Gap, and Many-Objective Robust Decision Making (MORDM). We propose a taxonomy of robustness frameworks to compare and contrast these approaches based on their methods of (1) alternative generation, (2) sampling of states of the world, (3) quantification of robustness measures, and (4) sensitivity analysis to identify important uncertainties. Building from the proposed taxonomy, we use a regional urban water supply case study in the Research Triangle region of North Carolina to illustrate the decision-relevant consequences that emerge from each of these choices. Results indicate that the methodological choices in the taxonomy lead to the selection of substantially different planning alternatives, underscoring the importance of an informed definition of robustness. Moreover, the results show that some commonly employed methodological choices and definitions of robustness can have undesired consequences when ranking decision alternatives. For the demonstrated test case, recommendations for overcoming these issues include: (1) decision alternatives should be searched rather than prespecified, (2) dominant uncertainties should be discovered through sensitivity analysis rather than assumed, and (3) a carefully elicited multivariate satisficing measure of robustness allows stakeholders to achieve their problem-specific performance requirements. This work emphasizes the importance of an informed problem formulation for systems facing challenging performance tradeoffs and provides a common vocabulary to link the robustness frameworks widely used in the field of water systems planning.

Hinrichsen, R. A., Hasselman, D. J., Ebbesmeyer, C. C., & Shields, B. A. (2013). The Role of Impoundments, Temperature, and Discharge on Colonization of the Columbia River Basin, USA, by Nonindigenous American Shad. *Transactions of the American Fisheries Society,* 142(4), 887-900. https://doi.org/10.1080/00028487.2013.788553

Ecologists have become increasingly aware of the combined effects of habitat disturbance and climate change on the establishment and proliferation of invasive species. Long-term data on the population of the invasive American Shad Alosa sapidissima in the U.S. portion of the Columbia River basin provide an opportunity to examine how habitat disturbances affect the abundance and spatial distribution of an invasive species in a heavily modified environment. After the establishment of American Shad in the Columbia River in the late 1800s, the drainage was transformed from its natural lotic state to a series of reservoirs, with concomitant changes to discharge and temperature regimes, which are confounded by climate change. As the Columbia River was dammed, American Shad extended its range and increased in abundance. A large and rapid increase in spawning population abundance (recruits per spawner = 63) followed completion of The Dalles Dam in 1957, which inundated Celilo Falls, a natural barrier to upriver American Shad migration. Regressions revealed that the annual percentage of American Shad migrating upstream from McNary Dam varied with water temperature and discharge (R-2 = 0.72), but not population density. When Atlantic coast rivers were dammed, however, American Shad lost spawning habitat and declined in abundance. Understanding the rapid colonization of the Columbia River by American Shad may reveal ways to help American Shad recolonize rivers where they are native. Understanding the roles of water temperature and discharge may allow us to project effects of climate change on the future distribution and abundance of American Shad in the Columbia River basin. Our results suggest that dam construction and alterations to the temperature and discharge regimes of the Columbia River have contributed to the increase in abundance and spatial distribution of American Shad. These changes might have improved the reproductive success of American Shad by providing access to additional spawning grounds and creating suitable juvenile rearing conditions.

Hirsch, R. M. (2011). A Perspective on Nonstationarity and Water Management. *Journal of the American Water Resources Association,* 47(3), 436-446. https://doi.org/10.1111/j.1752-1688.2011.00539.x

This essay offers some perspectives on climate-related nonstationarity and water resources. Hydrologists must not lose sight of the many sources of nonstationarity, recognizing that many of them may be of much greater magnitude than those that may arise from climate change. It is paradoxical that statistical and deterministic approaches give us better insights about changes in mean conditions than about the tails of probability distributions, and yet the tails are very important to water management. Another paradox is that it is difficult to distinguish between long-term hydrologic persistence and trend. Using very long hydrologic records is helpful in mitigating this problem, but does not guarantee success. Empirical approaches, using long-term hydrologic records, should be an important part of the portfolio of research being applied to understand the hydrologic response to climate change. An example presented here shows very mixed results for trends in the size of the annual floods, with some strong clusters of positive trends and a strong cluster of negative trends. The potential for nonstationarity highlights the importance of the continuity of hydrologic records, the need for repeated analysis of the data as the time series grow, and the need for a well-trained cadre of scientists and engineers, ready to interpret the data and use those analyses to help adjust the management of our water resources.

Jager, H. I., King, A. W., Gangrade, S., Haines, A., DeRolph, C., Naz, B. S., & Ashfaq, M. (2018). Will future climate change increase the risk of violating minimum flow and maximum temperature thresholds below dams in the Pacific Northwest? *Climate Risk Management,* 21, 69-84. https://doi.org/10.1016/j.crm.2018.07.001

Detecting and avoiding environmental thresholds that lead to catastrophic change in ecological communities is an important goal, and one that is especially challenging to address over broad geographic extents. Here, we conducted a regional-scale climate vulnerability assessment (RCVA) to quantify the risk of violating thermal and minimum-flow thresholds below reservoirs. Our analysis used hybrid (process-based and empirical) models of tailwater temperature and flow driven by 4-km downscaled CMIP5 climate projections. Downscaling employed a combination of process-based models, quantile mapping, and a non-linear 'reservoir' transform function. RCVA can be applied at regional scales without proprietary and data-intensive physical models of reservoir systems or ecological models of species that comprise tailwater communities. Using RCVA, we produced ensemble projections of risk and duration of extreme high-temperature or low-flow events below federal reservoirs in the Pacific Northwest (PNW), USA. Bayesian modeling of simulated results allowed us to evaluate differences between risk under a future and baseline scenario relative to model uncertainties and to quantify uncertainty in modeled risks. Based on assumptions that historical patterns of reservoir dynamics and operation will continue, and that regulatory thresholds will not change, the risk of thermal exceedance was projected to increase by an average of 0.27 and extend into late-spring and fall (average change in duration of 10.3 d). For flow, RCVA projected an increase of 0.07 in the average risk below-thresholds flows, with an average increase in duration of 4.6 d. Both results raise concerns that cold-water salmonids of the PNW will be at increased risk under a future climate scenario.

Jeuland, M., & Whittington, D. (2014). Water resources planning under climate change: Assessing the robustness of real options for the Blue Nile. *Water Resources Research,* 50(3), 2086-2107. https://doi.org/10.1002/2013wr013705

This article presents a methodology for planning new water resources infrastructure investments and operating strategies in a world of climate change uncertainty. It combines a real options (e.g., options to defer, expand, contract, abandon, switch use, or otherwise alter a capital investment) approach with principles drawn from robust decision-making (RDM). RDM comprises a class of methods that are used to identify investment strategies that perform relatively well, compared to the alternatives, across a wide range of plausible future scenarios. Our proposed framework relies on a simulation model that includes linkages between climate change and system hydrology, combined with sensitivity analyses that explore how economic outcomes of investments in new dams vary with forecasts of changing runoff and other uncertainties. To demonstrate the framework, we consider the case of new multipurpose dams along the Blue Nile in Ethiopia. We model flexibility in design and operating decisionsthe selection, sizing, and sequencing of new dams, and reservoir operating rules. Results show that there is no single investment plan that performs best across a range of plausible future runoff conditions. The decision-analytic framework is then used to identify dam configurations that are both robust to poor outcomes and sufficiently flexible to capture high upside benefits if favorable future climate and hydrological conditions should arise. The approach could be extended to explore design and operating features of development and adaptation projects other than dams. Key Points <list id="wrcr20813-list-0001" list-type="bulleted"> <list-item id="wrcr20813-li-0001">No planning alternative is likely to dominate across plausible future conditions <list-item id="wrcr20813-li-0002">We present a method for generating information for the selection of robust planning alternatives <list-item id="wrcr20813-li-0003">Downside and upside metrics can assist enhanced decision making

Jorgensen, J. C., Honea, J. M., McClure, M. M., Cooney, T. D., Engie, K., & Holzer, D. M. (2009). Linking landscape-level change to habitat quality: an evaluation of restoration actions on the freshwater habitat of spring-run Chinook salmon. *Freshwater Biology,* 54(7), 1560-1575. https://doi.org/10.1111/j.1365-2427.2009.02207.x

1. Conservation planning is often hampered by the lack of causal quantitative links between landscape characteristics, restoration actions and habitat conditions that impact the status of imperilled species. Here we present a first step toward linking actions on the landscape to the population status of endangered stream-type Chinook salmon (Oncorhynchus tshawytscha). 2. We developed relationships between land use, landscape characteristics and freshwater habitat of spring Chinook salmon in the Wenatchee River basin. Available data allowed us to find relationships that described water temperatures at several life stages (prespawning, egg incubation and summer rearing) and substratum characteristics, including fine sediments, cobble and embeddedness. Predictors included altitude, gradient, mean annual precipitation, total and riparian forest cover, road density, impervious surface and alluvium. We used a model averaging approach to account for parameter and model selection uncertainty. Key predictors were total forest cover and impervious surface area for prespawning and summer rearing temperatures; precipitation and stream gradients were important predictors of the percent of fine sediments in stream substrata. 3. We estimated habitat conditions using these relationships in three alternative landscape scenarios: historical, no restoration and one that included a set of restoration actions from local conservation planning. We found that prespawning and summer temperatures were estimated to be slightly higher historically relative to current conditions in dry sparsely forested areas, but lower in some important Chinook salmon spawning and rearing areas and lower in those locations under the restoration scenario. Fine sediments were lower in the historical scenario and were reduced as a consequence of restoration actions in two areas currently unoccupied by Chinook salmon that contain reaches with some potential for high quality spawning and rearing. Cobble and embeddedness in general were predicted to be higher historically and changed little as a result of restoration actions relative to current conditions. 4. This modelling framework converts suites of restoration actions into changes in habitat condition, thereby enabling restoration planners to evaluate alternative combinations of proposed actions. It also provides inputs to models linking habitat conditions to population status. This approach represents a first step in estimating impacts of restoration strategies, and can provide key information for conservation managers and planners.

Jorgensen, J. C., McClure, M. M., Sheer, M. B., & Munn, N. L. (2013). Combined Effects of Climate Change and Bank Stabilization on Shallow Water Habitats of Chinook Salmon. *Conservation Biology,* 27(6), 1201-1211. https://doi.org/10.1111/cobi.12168

Significant challenges remain in the ability to estimate habitat change under the combined effects of natural variability, climate change, and human activity. We examined anticipated effects on shallow water over low-sloped beaches to these combined effects in the lower Willamette River, Oregon, an area highly altered by development. A proposal to stabilize some shoreline with large rocks (riprap) would alter shallow water areas, an important habitat for threatened Chinook salmon (Oncorhynchus tshawytscha), and would be subject to U.S. Endangered Species Act-mandated oversight. In the mainstem, subyearling Chinook salmon appear to preferentially occupy these areas, which fluctuate with river stages. We estimated effects with a geospatial model and projections of future river flows. Recent (1999-2009) median river stages during peak subyearling occupancy (April-June) maximized beach shallow water area in the lower mainstem. Upstream shallow water area was maximized at lower river stages than have occurred recently. Higher river stages in April-June, resulting from increased flows predicted for the 2080s, decreased beach shallow water area 17-32%. On the basis of projected 2080s flows, more than 15% of beach shallow water area was displaced by the riprap. Beach shallow water area lost to riprap represented up to 1.6% of the total from the mouth to 12.9 km upstream. Reductions in shallow water area could restrict salmon feeding, resting, and refuge from predators and potentially reduce opportunities for the expression of the full range of life-history strategies. Although climate change analyses provided useful information, detailed analyses are prohibitive at the project scale for the multitude of small projects reviewed annually. The benefits of our approach to resource managers include a wider geographic context for reviewing similar small projects in concert with climate change, an approach to analyze cumulative effects of similar actions, and estimation of the actions' long-term effects.

Jung, I. W., & Chang, H. J. (2011). Assessment of future runoff trends under multiple climate change scenarios in the Willamette River Basin, Oregon, USA. *Hydrological Processes,* 25(2), 258-277. https://doi.org/10.1002/hyp.7842

We investigated trends in future seasonal runoff components in the Willamette River Basin (WRB) of Oregon for the twenty-first century. Statistically downscaled climate projections by Climate Impacts Group (CIG), eight different global climate model (GCM) simulations with two different greenhouse gas (GHG) emission scenarios, (A1B and B1), were used as inputs for the US Geological Survey's Precipitation Runoff Modelling System. Ensemble mean results show negative trends in spring (March, April and May) and summer (June, July and August) runoff and positive trends in fall (September, October and November) and winter (December, January and February) runoff for 2000-2099. This is a result of temperature controls on the snowpack and declining summer and increasing winter precipitation. With temperature increases throughout the basin, snow water equivalent (SWE) is projected to decline consistently for all seasons. The decreases in the centre of timing and 7-day low flows and increases in the top 5% flow are caused by the earlier snowmelt in spring, decreases in summer runoff and increases in fall and winter runoff, respectively. Winter runoff changes are more pronounced in higher elevations than in low elevations in winter. Seasonal runoff trends are associated with the complex interactions of climatic and topographic variables. While SWE is the most important explanatory variable for spring and winter runoff trends, precipitation has the strongest influence on fall runoff. Spatial error regression models that incorporate spatial dependence better explain the variations of runoff trends than ordinary least-squares (OLS) multiple regression models. Our results show that long-term trends of water balance components in the WRB could be highly affected by anthropogenic climate change, but the direction and magnitude of such changes are highly dependent on the interactions between climate change and land surface hydrology. This suggests a need for spatially explicit adaptive water resource management within the WRB under climate change.

Justice, C., White, S. M., McCullough, D. A., Graves, D. S., & Blanchard, M. R. (2017). Can stream and riparian restoration offset climate change. impacts to salmon populations? *Journal of Environmental Management,* 188, 212-227. https://doi.org/10.1016/j.jenvman.2016.12.005

Understanding how stream temperature responds to restoration of riparian vegetation and channel morphology in context of future climate change is critical for prioritizing restoration actions and recovering imperiled salmon populations. We used a deterministic water temperature model to investigate potential thermal benefits of riparian reforestation and channel narrowing to Chinook Salmon populations in the Upper Grande Ronde River and Catherine Creek basins in Northeast Oregon, USA. A legacy of intensive land use practices in these basins has significantly reduced streamside vegetation and increased channel width across most of the stream network, resulting in water temperatures that far exceed the optimal range for salmon growth and survival. By combining restoration scenarios with climate change projections, we were able to evaluate whether future climate impacts could be offset by restoration actions. A combination of riparian restoration and channel narrowing was predicted to reduce peak summer water temperatures by 6.5 degrees C on average in the Upper Grande Ronde River and 3.0 degrees C in Catherine Creek in the absence of other perturbations. These results translated to increases in Chinook Salmon parr abundance of 590% and 67% respectively. Although projected climate change impacts on water temperature for the 2080s time period were substantial (i.e., median increase of 2.7 degrees C in the Upper Grande Ronde and 1.5 degrees C in Catherine Creek), we predicted that basin-wide restoration of riparian vegetation and channel width could offset these impacts, reducing peak summer water temperatures by about 3.5 degrees C in the Upper Grande Ronde and 1.8 degrees C in Catherine Creek. These results underscore the potential for riparian and stream channel restoration to mitigate climate change impacts to threatened salmon populations in the Pacific Northwest.

Kang, B., & Ramirez, J. A. (2007). Response of streamflow to weather variability under climate change in the Colorado Rockies. *Journal of Hydrologic Engineering,* 12(1), 63-72. https://doi.org/10.1061/(asce)1084-0699(2007)12:1(63)

We examine the response of streamflow to long-term rainfall variability under climate change by coupling downscaled global climate model precipitation to a distributed hydrologic model. We use daily output of the coupled global climate model (CGCM2) of the Canadian Centre for Climate Modelling and Analysis corresponding to the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios B2 scenario. The B2 scenario envisions slower population growth (10.4 billion by 2100) with a more rapidly evolving economy and more emphasis on environmental protection. We use the Hydrologic Modeling System of the Hydrologic Engineering Center for distributed hydrologic modeling. Because of the incongruence between the spatial scale of the CGCM2 output and that of the hydrologic model, a new space-time stochastic random cascade model was implemented in order to downscale the CGCM2 precipitation. The downscaling model accounts for the observed spatial intermittency of precipitation as well as for the self-similar scaling structure of its spatial distribution. For the South Platte basin, results show that the distribution of peak flow rate is more sensitive to the spatial variability of rainfall than total runoff volume. Results also show that the relative impact of long-term rainfall variation associated with climate change on total runoff and peak flow can be much greater than the magnitude of the rainfall variation itself, and that the magnitude of the impact depends strongly on the magnitude of the associated change in evapotranspiration.

Khedun, C. P., & Singh, V. P. (2013). *Engineering Water Security under Climate Variability and Change*. No URL available.

Access to water is still a major problem around the world, despite the fact that less than 10% of annual discharge is actually withdrawn by humans. Nearly 80% of the world's population is exposed to high levels of threat to water security. A large percentage of the world's populations live in areas that are subject to extreme seasonal changes in precipitation and evaporation. Climate variability and change represent formidable challenges for the water resources management community. In this article the influence of climate variability and change on the hydrological cycle and hence water availability is discussed, and how water security can be engineering in light of these new challenges. Traditional engineering education and practices may not be sufficient; research, technological innovations, changes to infrastructure design and development, and education should receive maximum attention to ensure water security in the face of these impending challenges.

Kilgore, R., Herrmann, G., Thomas, W. O., & Thompson, D. (2017). Incorporating Climate Change, Risk, and Resilience into Hydrologic Design Procedures. In *World Environmental and Water Resources Congress 2017: Groundwater, Sustainability, and Hydro-Climate/Climate Change.* C. N. Dunn & B. VanWeele (Eds.), (pp. 317-330) https://doi.org/10.1061/9780784480618.031

In 2016, the Federal Highway Administration (FHWA) completed an effort to provide new design guidance for engineers and designers of hydraulic structures, drainage facilities, and highway encroachments that incorporates the best actionable climate science and risk assessment approaches. The new guidance is known as Hydraulic Engineering Circular Number 17 (HEC-17) "Highways in the River Environment - Floodplains, Extreme Events, Risk, and Resilience." This paper summarizes selected features of the guidance including the incorporation of the uncertainty associated with hydrologic data and models into hydrologic design. Specifically, the paper describes the use of confidence limits to build more resilient infrastructure and how to incorporate climate change into hydrologic design within a framework of different levels of effort that depend on the nature of the project. Example computations are provided to illustrate key concepts.

Kirsch, B. R., Characklis, G. W., & Zeff, H. B. (2013). Evaluating the Impact of Alternative Hydro-Climate Scenarios on Transfer Agreements: Practical Improvement for Generating Synthetic Streamflows. *Journal of Water Resources Planning and Management,* 139(4), 396-406. https://doi.org/10.1061/(asce)wr.1943-5452.0000287

Utilities are increasingly considering the use of temporary water transfers to augment their supplies during periods of drought, an alternative that is often less expensive than expanding safe yields through new infrastructure. Understanding the volume and timing of transfers is important for developing contracts between buyer and seller and can be challenging due to the transient nature of drought, a situation complicated by the uncertainties associated with climate change. While transfer arrangements have received some attention in the literature, the effects of climate change on such agreements remain unexplored. This paper investigates these impacts using an improved method for developing new hydro-climate scenarios. A technique for producing stochastic time series of inflows is described, one which effectively replicates the autocorrelation present in the historic record. Unlike autoregressive (and similar) models that assume complete stationarity, the modified fractional Gaussian noise (mFGN) method preserves the seasonal patterns in the correlation structure, thereby providing some advantages when modifying historical streamflow records to reflect alternative hydro-climate scenarios. Alternative scenarios are developed for the Research Triangle region of North Carolina, an area with several utilities currently seeking to use a system of risk-based transfer agreements as a means to meet demand during droughts. This study simulates hydrologic conditions and transfer activity from 2010 to 2025 under a variety of climate scenarios. Results indicate that increased variability in inflows, with no change in the mean, corresponds to slight increases in transfer activity. However, when increased variability is paired with modest decreases in expected inflows (7%), transfer activity is doubled.

Kurylyk, B. L., MacQuarrie, K. T. B., Linnansaari, T., Cunjak, R. A., & Curry, R. A. (2015). Preserving, augmenting, and creating cold-water thermal refugia in rivers: concepts derived from research on the Miramichi River, New Brunswick (Canada). *Ecohydrology,* 8(6), 1095-1108. https://doi.org/10.1002/eco.1566

Summer water temperatures are rising in many river systems in North America, and this warming trend is projected to intensify in the coming decades. Cold-water fish may alleviate thermal stress in summer by aggregating in discrete cold-water plumes that provide thermal refuge from high ambient river temperatures. Reliance on cold-water thermal refugia is expected to increase in a warming climate, and many river reaches already lack suitable thermal refugia as a result of an absence of thermal diversity. A comprehensive fish management strategy could proactively address this imminent threat to cold-water fish populations across North America by preserving existing thermal refugia, augmenting thermal anomalies to improve performance as refugia, and creating new thermal refugia in uniformly warm river reaches. We provide practical recommendations on how these measures can be accomplished based on insight derived from recent research focused on the Miramichi River, New Brunswick. Opportunities include limiting land use change, construction aggregate extraction (e.g. sand and gravel pits), and groundwater pumping/consumption. Existing thermal anomalies can be enhanced by controlling advective thermal mixing between cold-water tributaries and the river mainstem flow, installing riparian shading, and adding temporary structures for protection from avian predators. New refugia can be created by temporarily pumping groundwater to discrete points within the river during periods of thermal stress. These concepts are discussed in the context of a comprehensive thermal refugia management strategy.

Lane, S. N., Tayefi, V., Reid, S. C., Yu, D., & Hardy, R. J. (2007). Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms,* 32(3), 429-446. https://doi.org/10.1002/esp.1404

This paper uses numerical simulation of flood inundation based on a coupled one-dimensional/two-dimensional treatment to explore the impacts upon flood extent of both long-term climate changes, predicted to the 2050s and 2080s, and short-term river channel changes in response to sediment delivery, for a temperate upland gravel-bed river. Results show that 16 months of measured in-channel sedimentation in an upland gravel-bed river cause about half of the increase in inundation extent that was simulated to arise from climate change. Consideration of the joint impacts of climate change and sedimentation emphasized the non-linear nature of system response, and the possibly severe and synergistic effects that come from combined direct effects of climate change and sediment delivery. Such effects are likely to be exacerbated further as a result of the impacts of climate change upon coarse sediment delivery. In generic terms, these processes are commonly overlooked in flood risk mapping exercises and are likely to be important in any river system where there are high rates of sediment delivery and long-term transfer of sediment to floodplain storage (i.e. alluviation involving active channel aggradation and migration). Similarly, attempts to reduce channel migration through river bank stabilization are likely to exacerbate this process as without bank erosion, channel capacity cannot be maintained. Finally, many flood risk mapping studies rely upon calibration based upon combining contemporary bed surveys with historical flood outlines, and this will lead to underestimation of the magnitude and frequency of floodplain inundation in an aggrading system for a flood of a given magnitude.

Leach, J. A., & Moore, R. D. (2019). Empirical Stream Thermal Sensitivities May Underestimate Stream Temperature Response to Climate Warming. *Water Resources Research,* 55(7), 5453-5467. https://doi.org/10.1029/2018wr024236

Stream temperature has been increasing in tandem with air temperature, with potentially negative impacts on cold-water fish such as salmon. Assessing future stream temperature change is critical for developing effective management responses. Empirical models of stream thermal sensitivity generally predict less future warming compared to physically based models. Here we reconcile these discrepancies by using a process-based hydrology and temperature model to simulate daily flow and water temperature for forested headwater catchments in a maritime region under both historic and projected future climatic conditions. The primary reason that the empirical approach underestimates thermal response to climate change is that it does not account for thermal memory in the catchment, especially related to the effect of snow cover. Empirical thermal sensitivities thus may underestimate stream temperature response to future climate warming. In addition, groundwater-fed streams may only resist warming in the short-medium term, due to lagged response of groundwater temperature. More process-based understanding and modeling of stream thermal regimes is needed to effectively manage aquatic ecosystems.

Ledbetter, R., Prudhomme, C., & Arnell, N. (2012). A method for incorporating climate variability in climate change impact assessments: Sensitivity of river flows in the Eden catchment to precipitation scenarios. *Climatic Change,* 113(3-4), 803-823. https://doi.org/10.1007/s10584-011-0386-0

Interest in the impacts of climate change is ever increasing. This is particularly true of the water sector where understanding potential changes in the occurrence of both floods and droughts is important for strategic planning. Climate variability has been shown to have a significant impact on UK climate and accounting for this in future climate change projections is essential to fully anticipate potential future impacts. In this paper a new resampling methodology is developed which includes the variability of both baseline and future precipitation. The resampling methodology is applied to 13 CMIP3 climate models for the 2080s, resulting in an ensemble of monthly precipitation change factors. The change factors are applied to the Eden catchment in eastern Scotland with analysis undertaken for the sensitivity of future river flows to the changes in precipitation. Climate variability is shown to influence the magnitude and direction of change of both precipitation and in turn river flow, which are not apparent without the use of the resampling methodology. The transformation of precipitation changes to river flow changes display a degree of non-linearity due to the catchment's role in buffering the response. The resampling methodology developed in this paper provides a new technique for creating climate change scenarios which incorporate the important issue of climate variability.

Lee, S. Y., Fitzgerald, C. J., Hamlet, A. F., & Burges, S. J. (2011). Daily Time-Step Refinement of Optimized Flood Control Rule Curves for a Global Warming Scenario. *Journal of Water Resources Planning and Management-ASCE,* 137(4), 309-317. https://doi.org/10.1061/(asce)wr.1943-5452.0000125

Pacific Northwest temperatures have warmed by 0.8 degrees C since 1920 and are predicted to increase in the 21st century. Streamflow timing shifts associated with climate change would degrade the water resources system performance for climate change scenarios using existing system operation policies for the Columbia River Basin. To mitigate the hydrologic impacts of anticipated climate change on this complex water resource system, optimized flood control operating rule curves were developed at a monthly time step in a previous study and were evaluated with a monthly time-step simulation model. Here, a daily time-step simulation model is used over a smaller portion of the domain to evaluate and refine the optimized flood-control curves derived from monthly time-step analysis. Daily time-step simulations demonstrate that maximum evacuation targets for flood control derived from the monthly analysis were remarkably robust. However, the evacuation schedules for Libby and Duncan Dams from February to April conflicted with Kootenay Lake level requirements specified in the 1938 International Joint Commission Order on Kootenay Lake. We refined the flood rule curves derived from monthly analysis by creating a gradual evacuation schedule, keeping the timing and magnitude of maximum evacuation the same as in the monthly analysis. After these refinements, the performance at monthly timescales reported in our previous study proved robust at daily timescales. Owing to a decrease in July storage deficits, additional benefits such as more revenue from hydropower generation and more July and August outflow for fish augmentation were observed when the optimized flood-control curves were used for a climate-change scenario.

Lee, S. Y., Fullerton, A. H., Sun, N., & Torgersen, C. E. (2020). Projecting spatiotemporally explicit effects of climate change on stream temperature: A model comparison and implications for coldwater fishes. *Journal of Hydrology,* 588. https://doi.org/10.1016/j.jhydrol.2020.125066

Conservation planners and resource managers seek information about how the availability and locations of cold-water habitats will change in the future and how these predictions vary among models. We used a physical process-based model to demonstrate the implications of climate change for streamflow and water temperature in two watersheds with distinctive flow regimes: the Snoqualmie watershed (WA) and Siletz watershed (OR), USA. Our model incorporated a downscaled ensemble of global climate model outputs and was calibrated with in situ and remotely sensed water temperatures. We compared predictions from our processed-based model to those from a publicly available and widely used statistical model. The process-based model projected greater changes in summer maximum water temperatures for the mixed-rain-snow Snoqualmie watershed than for the raindominated Siletz watershed as a result of the near-complete loss of winter snowpack and significant reduction in summer flow in the Snoqualmie watershed expected by the 2080s. Both models projected generally similar future spatial patterns of maximum water temperature in the two rivers, with cool reaches distributed farther upstream and fewer in number. However, the process-based model projected higher spatial

heterogeneity in water temperature due to our spatially explicit simulation of streamflow and because we calibrated the model with spatially continuous remotely sensed water temperature data. We used stream temperature projections to assess the vulnerability of Pacific salmon and trout to changes in the spatial distribution of cold-water habitats during August by the 2080 s. Results suggest that salmonids may have fewer summertime cold-water habitats in both watersheds. Projected stream warming may further limit particular species and life stages, especially in the Snoqualmie watershed. Our comparison of models highlights the importance of considering what might be gained by using a process-based model for evaluating and prioritizing management actions that mitigate climate impacts on cold-water habitats for stream fishes.

Lee, S. Y., Hamlet, A. F., Fitzgerald, C. J., & Burges, S. J. (2009). Optimized Flood Control in the Columbia River Basin for a Global Warming Scenario. *Journal of Water Resources Planning and Management,* 135(6), 440-450. https://doi.org/10.1061/(asce)0733-9496(2009)135:6(440)

Anticipated future temperature changes in the mountainous U. S. Pacific Northwest will cause reduced spring snow pack, earlier melt, earlier spring peak flow and lower summer flow in transient rain-snow and snowmelt dominant river basins. In the context of managed flood control, these systematic changes are likely to disrupt the balance between flood control and reservoir refill in existing reservoir systems. To adapt to these hydrologic changes, refill timing and evacuation requirements for flood control need to be modified. This work poses a significant systems engineering problem, especially for large, multiobjective water systems. An existing optimization/simulation procedure is refined for rebalancing flood control and refill objectives for the Columbia River Basin for anticipated global warming. To calibrate the optimization model for the 20th century flow, the objective function is tuned to reproduce the current reliability of reservoir refill, while providing comparable levels of flood control to those produced by current flood control practices. After the optimization model is calibrated using the 20th century flow the same objective function is used to develop flood control curves for a global warming scenario which assumes an approximately 2 C increase in air temperature. Robust decreases in system storage deficits are simulated for the climate change scenario when optimized flood rule curves replace the current flood control curves, without increasing monthly flood risks.

Liu, J., Kattel, G., Arp, H. P. H., & Yang, H. (2015). Towards threshold-based management of freshwater ecosystems in the context of climate change. *Ecological Modelling,* 318, 265-274. https://doi.org/10.1016/j.ecolmodel.2014.09.010

Climate change is an increasing threat to freshwater ecosystem goods and services. We review recent research regarding the direct and indirect impacts of climate change on freshwater ecosystems and the severity of their undesirable effects on ecosystem processes and services. Appropriate management strategies are needed to mitigate the long-term or irreversible losses of ecosystem services caused by climate change. To address this, this review puts forward a threshold-based management framework as a potential platform for scientists, decision makers and stakeholders of freshwater ecosystems to work together in reducing risks from climate change. In this framework, the susceptibility of local freshwater ecosystems to change beyond thresholds is continuously investigated and updated by scientists, used to design policy targets by decision makers, and used to establish mitigation measures by local stakeholders.

Lopez, A., Fung, F., New, M., Watts, G., Weston, A., & Wilby, R. L. (2009). From climate model ensembles to climate change impacts and adaptation: A case study of water resource management in the southwest of England. *Water Resources Research,* 45. https://doi.org/10.1029/2008wr007499

The majority of climate change impacts and adaptation studies so far have been based on at most a few deterministic realizations of future climate, usually representing different emissions scenarios. Large ensembles of climate models are increasingly available either as ensembles of opportunity or perturbed physics ensembles, providing a wealth of additional data that is potentially useful for improving adaptation strategies to climate change. Because of the novelty of this ensemble information, there is little previous experience of practical applications or of the added value of this information for impacts and adaptation decision making. This paper evaluates the value of perturbed physics ensembles of climate models for understanding and planning public water supply under climate change. We deliberately select water resource models that are already used by water supply companies and regulators on the assumption that uptake of information from large ensembles of climate models will be more likely if it does not involve significant investment in new modeling tools and methods. We illustrate the methods with a case study on the Wimbleball water resource zone in the southwest of England. This zone is sufficiently simple to demonstrate the utility of the approach but with enough complexity to allow a variety of different decisions to be made. Our research shows that the additional information contained in the climate model ensemble provides a better understanding of the possible ranges of future conditions, compared to the use of single-model scenarios. Furthermore, with careful presentation, decision makers will find the results from large ensembles of models more accessible and be able to more easily compare the merits of different management options and the timing of different adaptation. The overhead in additional time and expertise for carrying out the impacts analysis will be justified by the increased quality of the decision-making process. We remark that even though we have focused our study on a water resource system in the United Kingdom, our conclusions about the added value of climate model ensembles in guiding adaptation decisions can be generalized to other sectors and geographical regions.

Macura, V., Stefunkova, Z., & Skrinar, A. (2016). Determination of the Effect of Water Depth and Flow Velocity on the Quality of an In-Stream Habitat in Terms of Climate Change. *Advances in Meteorology,* 2016. https://doi.org/10.1155/2016/4560378

The study is focused on the objectification of an assessment of the quality of an in-stream habitat in mountain and piedmont streams by the decision-making Instream Flow Incremental Methodology (IFIM) due to climate change. The quality of the habitat was assessed on the basis of a bioindication, represented by ichthyofauna. Sixty-four reaches of 47 watercourses in five river basins in Slovakia, in which ichthyologic, topographic, and hydraulic measurements were performed, were evaluated. The effect of the physical characteristics of the stream channel on the quality of the in-stream habitat has been verified on a number of reference reaches in which the measurements were performed at different water levels. From the set of the data measured, an analysis aimed at determining the impact of individual characteristics on the quality of an in-stream habitat has been carried out. The results show the optimum ratio of the weights of the flow velocity and water depth for an assessment of the quality of an in-stream habitat due to climate change.

Mateus, M. C., & Tullos, D. (2017). Reliability, Sensitivity, and Vulnerability of Reservoir Operations under Climate Change. *Journal of Water Resources Planning and Management,* 143(4). https://doi.org/10.1061/(asce)wr.1943-5452.0000742

Climate change may critically impair the performance of reservoirs in meeting operational objectives, but reservoirs may also aid in adapting to climate change. To understand how the reliabilities, sensitivities, and vulnerabilities of reservoir operations vary across hydrogeologic settings, a bottom-up approach was applied to investigate the reliability of two water resources systems in the future. To represent the uncertainty associated with future streamflow, global climate model projections were integrated with a formal Bayesian uncertainty analysis and groundwater-surface water hydrologic modeling. Finally, the effectiveness of variable rule curves for mitigating the effects of climate change was evaluated. Increasing air temperature appeared to reduce the reliability of meeting summer environmental flow targets in the future by 42 and 12% for the groundwater basin and surface water basin, respectively, but had negligible impacts on reservoir refilling and flood regulation. Variable rule curves mitigated the impact of climate change on summer flow target reliability without compromising flood risk reduction. Differences in subbasin sensitivity to changing climate were evident across the two hydrogeologic settings, and uncertainty associated with modeling groundwater resources and decision thresholds were identified, with implications for reliability assessments in other basins.

Mauger, G. S. (2018). Supporting Climate-Resilient Design for In-Stream Restoration and Fish Passage Projects. Retrieved from https://www.sciencebase.gov/catalog/item/5b50b1d5e4b06a6dd185e103

The goal of this project is to support climate-resilient design for culvert and fish habitat restoration projects in Washington. Through collaboration with the Washington Department of Fish and Wildlife (WDFW), researchers will develop an interactive website that will provide the best available science on projections of future stream discharges and channel width for the state. These projections will be provided at the site level, and will also include estimates of the probability that a given culvert will fail to meet the design standard for fish passage during its service life. While WDFW has developed an internal tool to support climate-resilient culvert design, the tool needs to be updated to reflect the latest science. The purpose of this project is to address those issues and increase the utility and accessibility of the existing web tool. The final, publicly-available website will support engineers, landscape architects, restoration ecologists, and others involved in the design of culverts and stream restoration projects in Washington State.

Mauger, G. S., Lee, S.-Y., Won, J., Byun, K., & Hamlet, A. F. (2018). *Climate robust culvert design: Probabilistic estimates of fish passage impediments for Washington State.* Skagit Climate Science Consortium Retrieved from https://cig.uw.edu/wp-content/uploads/sites/2/2018/07/Final_Report_SC2-Culverts_FINAL.compressed_3.pdf

This report describes a new tool that is designed to support climate-robust culvert design. In addition, the report describes an evaluation of the meteorological and streamflow datasets that are the basis for the tool, with the goal of supporting the use and interpretation of the results.

Maurer, E. P., Kayser, G., Doyle, L., & Wood, A. W. (2018). Adjusting Flood Peak Frequency Changes to Account for Climate Change Impacts in the Western United States. *Journal of Water Resources Planning and Management,* 144(3). https://doi.org/10.1061/(asce)wr.1943-5452.0000903

One consistent projection for the western United States has been for increasing peak streamflow as the global climate warms. Although past studies have characterized some aspects of future streamflow projections, this effort exploits new data sources to estimate changing peak flow frequency based on output from many climate projections, which drive a physically-based hydrology model. Using historic and projected future streamflow simulations at 421 sites across the western United States, changes in peak flows for common recurrence intervals are estimated. A parameter relating the recurrence interval needed for design in the present to produce a future required recurrence interval is derived and mapped across the United States, illustrating a method for adapting design to a changing hydrologic setting. For this demonstration, using a higher business-as-usual greenhouse gas emissions pathway, peak flow increases were proportionately larger for the more rare 100-year (or 1% exceedance) event than the 10-year event. Compared to 1971-2000, the domain-wide peak flow magnitude is projected to increase by 14-19% for early 21st century and 31-43% by the end of the 21st century, depending on recurrence interval. Impacts under lower emissions pathways will be more modest (or occur further in the future). In terms of return period, by the end of the 21st century, the 100-year event of the late twentieth century is projected to be approximately a 40-year event, representing a 2.5-fold increase in occurrence probability. This approach offers a strategy for regional planners to incorporate these projected changes into design based on flood flow frequency.

Mawdsley, J. (2011). Design of conservation strategies for climate adaptation. *Wiley Interdisciplinary Reviews-Climate Change,* 2(4), 498-515. https://doi.org/10.1002/wcc.127

A growing literature emphasizes the importance of managing the adverse effects of climate change on animal and plant species, biological communities, natural areas, and ecosystems. Although replete with general 'climate adaptation' strategies, this literature provides relatively limited guidance on translating these strategies into actionable conservation prescriptions. This review synthesizes information from the conservation planning and climate adaptation literature, including climate adaptation plans developed in Canada, England, Mexico, South Africa, and USA, and presents elements of a general approach for developing actionable adaptation measures for wildlife species and conservation areas. Grounded in an adaptive management framework, this approach incorporates existing conservation tools for land and water protection, land and water management, species conservation, and monitoring, and also integrates new information from climate models, sensitivity analyses, and vulnerability assessments for species and ecosystems.

McKean, J., & Tonina, D. (2013). Bed stability in unconfined gravel bed mountain streams: With implications for salmon spawning viability in future climates. *Journal of Geophysical Research-Earth Surface,* 118(3), 1227-1240. https://doi.org/10.1002/jgrf.20092

Incubating eggs of autumn-spawning Chinook salmon (Oncorhynchus tshawytscha) could be at risk of midwinter high flows and substrate scour in a changing climate. A high-spatial-resolution multidimensional hydrodynamics model was used to assess the degree of scour risk in low-gradient unconfined gravel bed channels that are the favored environment for autumn-spawning salmon in mountain watersheds such as the Middle Fork Salmon River (MFSR), Idaho. In one of the most important

MFSR spawning tributaries, near-bed shear stresses were relatively low at all discharges from base flows to 300% of bankfull. The highest stresses were found only in small areas of the central flow core and not at spawning sites. Median shear stresses did not increase in overbank flow conditions because poor channel confinement released the excess water into adjacent floodplains. Channel and floodplain topography, rather than discharge, control the maximum near-bed shear stresses. Over the modeled range of discharges, similar to 2% of the total surface area of the main stem channel bed was predicted to be mobile. Even in known spawning areas, where shear stresses are higher, 20% of the spawning surface area was mobile during overbank flows with a 2year recurrence interval. Field measurements of little gravel transport during flows that were 93% of bankfull support the numerical model predictions. Regardless of some uncertainty in future climates in these watersheds, there appears to be relatively limited risk of extensive scour at salmon spawning sites in any likely hydrologic regimes.

Merriam, E. R., & Petty, J. T. (2019). Stream channel restoration increases climate resiliency in a thermally vulnerable Appalachian river. *Restoration Ecology,* 27(6), 1420-1428. https://doi.org/10.1111/rec.12980

We quantified stream temperature response to in-stream habitat restoration designed to improve thermal suitability and resiliency of a high-elevation Appalachian stream known to support a temperature-limited brook trout population. Our specific objectives were to determine if: (1) construction of deep pools created channel unit-scale thermal refugia and (2) reach scale stream channel reconfiguration reduced peak water temperatures along a longitudinal continuum known to be highly susceptible to summer-time warming. Contrary to expectations, constructed pools did not significantly decrease channel unit-scale summer water temperatures relative to paired control sites. This suggests that constructed pools did not successfully intercept a cool groundwater source. However, we did find a significant effect of stream channel restoration on reach-scale thermal regimes. Both mean and maximum daily stream temperatures experienced significantly reduced warming trends in restored sections relative to control sections. Furthermore, we found that restoration efforts had the greatest effect on stream temperatures downstream of large tributaries. Restoration appears to have significantly altered thermal regimes within upper Shavers Fork, largely in response to changes in channel morphology that facilitated water movement below major cold-water inputs. Decreased longitudinal warming will likely increase the thermal resiliency of the Shavers Fork main-stem, sustaining the ability of these key large river habitats to continue supporting critical metapopulation processes (e.g. supplemental foraging and dispersal among tributary populations) in the face of climate change.

Miller, W. P., Butler, R. A., Piechota, T., Prairie, J., Grantz, K., & DeRosa, G. (2012). Water Management Decisions Using Multiple Hydrologic Models within the San Juan River Basin under Changing Climate Conditions. *Journal of Water Resources Planning and Management,* 138(5), 412-420. https://doi.org/10.1061/(asce)wr.1943-5452.0000237

A modified version of the U. S. Bureau of Reclamation (Reclamation) long-term planning model, Colorado River Simulation System (CRSS), is used to evaluate whether hydrologic model choice has an impact on critical decision variables within the San Juan River Basin when evaluating potential effects of climate change through 2099. The distributed variable infiltration capacity (VIC) model and the lumped National Weather Service (NWS) River Forecast System (RFS) were each used to project future streamflow; these projections of streamflow were then used to force Reclamation's CRSS model over the San Juan River Basin. Both hydrologic models were compared to evaluate whether or not uncertainty in climatic input generated from general circulation models outweighed differences between the hydrologic models. Differences in methodologies employed by each hydrologic model had a significant effect on projected streamflow within the basin. Both models project decreased water availability under changing climate conditions within the San Juan River Basin, but disagree on the magnitude of the decrease. On average, total naturalized inflow within the San Juan River Basin into the Navajo Reservoir is approximately 15% higher using inflows derived using the VIC model than those inflows developed using the RFS model; average projected tributary inflow from the San Juan River Basin to the Colorado River is approximately 25% higher using inflows derived by using the VIC model than those inflows developed by using the RFS. Overall, there is a higher risk and magnitude of shortage within the San Juan River Basin using streamflow developed with the RFS model as compared with inflow scenarios developed by using the VIC model. Model choice was found to have a significant effect on the evaluation of climate change impacts over the San Juan River Basin.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., . . . Krysanova, V. (2015). On Critiques of "Stationarity is Dead: Whither Water Management?". *Water Resources Research,* 51(9), 7785-7789. https://doi.org/10.1002/2015wr017408

We review and comment upon some themes in the recent stream of critical commentary on the assertion that "stationarity is dead," attempting to clear up some misunderstandings; to note points of agreement; to elaborate on matters in dispute; and to share further relevant thoughts.

Moody, P., & Brown, C. (2013). Robustness indicators for evaluation under climate change: Application to the upper Great Lakes. *Water Resources Research,* 49(6), 3576-3588. https://doi.org/10.1002/wrcr.20228

Given the range of future uncertainty, there is increasing interest in developing and evaluating water management strategies that are robust to an uncertain future. As part of a process termed "decision scaling,'' a climate response function was developed to isolate the impact of climate change on a water system in terms of hazards identified by stakeholders. The climate response function was then used to evaluate system performance over a wide range of climate conditions and to define robustness indicators. The robustness indicators, which measure system performance as a function of climate state, are conditioned on explicit assumptions about climate variable probability distributions. To illustrate this process, it is applied to the upper Great Lakes to evaluate system robustness related to water management decisions and assess the impact of climate probability assumptions. The robustness indicators were used to identify decisions that outperformed other courses of action regardless of assumptions of future climate probabilities.

Morsy, M. M., Shen, Y., Sadler, J. M., Chen, A. B., Zahura, F. T., & Goodall, J. L. (2019). Incorporating Potential Climate Change Impacts in Bridge and Culvert Design. Retrieved from http://www.virginiadot.org/vtrc/main/online_reports/pdf/20-r13.pdf

This project examined the potential impact of changing climatic conditions on structural designs in Virginia. A methodology was developed for producing intensity-duration-frequency (IDF) curves verified against the standard Atlas 14 values. The results suggest increases in rainfall depth for a 24-hour rainfall event. The second objective used a 2-dimensional hydrodynamic model to assess increased rainfall volumes on peak runoff volumes, suggesting smaller watersheds have a constant relationship between peak runoff and watershed size, while larger watersheds have less than 1% increase in peak runoff as the watershed size increases. The third objective illustrated average annual risk over the lifespan of a culvert and a bridge. Finally, the IDF approach showed significant variability across individual stations, but no obvious spatial trend. It is recommended that VDOT use the findings from this study to update the design standards involving storm water runoff and stream flows. When VDOT assets are designed using rainfall data, the values should be increased to account for the greater rainfall predicted and reported in this study. When VDOT assets are designed using discharge data not derived from rainfall, the values should be increased to account for the greater discharges predicted and reported in this study.

Mote, P. W., Parson, E. A., Hamlet, A. F., Keeton, W. S., Lettenmaier, D., Mantua, N., . . . Snover, A. K. (2003). Preparing for Climatic Change: The Water, Salmon, and Forests of the Pacific Northwest. *Climatic Change,* 61(1), 45-88. https://doi.org/10.1023/A:1026302914358

The impacts of year-to-year and decade-to-decade climatic variations on some of the Pacific Northwest's key natural resources can be quantified to estimate sensitivity to regional climatic changes expected as part of anthropogenic global climatic change. Warmer, drier years, often associated with El Niño events and/or the warm phase of the Pacific Decadal Oscillation, tend to be associated with below-average snowpack, streamflow, and flood risk, below-average salmon survival, below-average forest growth, and above-average risk of forest fire. During the 20th century, the region experienced a warming of 0.8 °C. Using output from eight climate models, we project a further warming of 0.5–2.5 °C (central estimate 1.5 °C) by the 2020s, 1.5–3.2°C (2.3 °C) by the 2040s, and an increase in precipitation except in summer. The foremost impact of a warming climate will be the reduction of regional snowpack, which presently supplies water for ecosystems and human uses during the dry summers. Our understanding of past climate also illustrates the responses of human management systems to climatic stresses, and suggests that a warming of the rate projected would pose significant challenges to the management of natural resources. Resource managers and planners currently have few plans for adapting to or mitigating the ecological and economic effects of climatic change.

Naiman, R. J., Latterell, J. J., Pettit, N. E., & Olden, J. D. (2008). Flow variability and the biophysical vitality of river systems. *Comptes Rendus Geoscience,* 340(9-10), 629-643. https://doi.org/10.1016/j.crte.2008.01.002

We illustrate the fundamental importance of fluctuations in natural water flows to the long-term sustainability and productivity of riverine ecosystems and their riparian areas. Natural flows are characterized by temporal and spatial heterogeneity in the magnitude, frequency, duration, timing, rate of change, and predictability of discharge. These characteristics, for a specific river or a collection of rivers within a defined region, shape species life histories over evolutionary (millennial) time scales as well as structure the ecological processes and productivity of aquatic and riparian communities. Extreme events - uncommon floods or droughts - are especially important in that they either reset or alter physical and chemical conditions underpinning the long-term development of biotic communities. We present the theoretical rationale for maintaining flow variability to sustain ecological communities and processes, and illustrate the importance of flow variability in two case studies - one from a semi-arid savanna river in South Africa and the other from a temperate rainforest river in North America. We then discuss the scientific challenges of determining the discharge patterns needed for environmental sustainability in a world where rivers, increasingly harnessed for human uses, are experiencing substantially altered flow characteristics relative to their natural states.

Naman, S. M., Rosenfeld, J. S., Jordison, E., Kuzyk, M., & Eaton, B. C. (2020). Exploitation of Velocity Gradients by Sympatric Stream Salmonids: Basic Insights and Implications for Instream Flow Management. *North American Journal of Fisheries Management,* 40(2), 320-329. https://doi.org/10.1002/nafm.10411

Hydraulic heterogeneity can strongly influence habitat selection by stream fishes. Velocity gradients created by channel roughness and flow obstructions may be particularly important for species that feed on drifting invertebrates, where maintaining focal points in low-velocity microhabitats adjacent to faster water allows fish to scan a larger water volume for prey while minimizing swimming costs. However, these velocity gradients are rarely integrated into habitat suitability criteria used for defining instream flow requirements, which are generally based on mean column velocity measurements at the focal point location. It is also unclear how velocity gradient exploitation differs among sympatric drift-feeding species. We measured the use of velocity gradients by two sympatric juvenile salmonids, Coho Salmon Oncorhynchus kisutch and steelhead O. mykiss, in a midorder cobble-boulder-dominated river. We compared focal point velocities of fish to adjacent velocities within their foraging area and compared the magnitude of velocity and kinetic energy gradients between species. We then explored how lateral velocity gradients may bias instream flow assessments by deriving two sets of velocity habitat suitability curves (HSCs): conventional HSCs using average water column velocities measured at focal point locations and spatially averaged HSCs incorporating adjacent velocities (four body lengths from focal points). These contrasting HSCs were then used as input into the physical habitat simulation model to predict the influence of flow on habitat availability. Both species often used focal velocities that were lower than adjacent points, but the magnitude of these velocity gradients was higher for steelhead, consistent with known differences in foraging behavior, habitat selection, and physiology. Incorporating adjacent velocities into HSCs resulted in a 40% (steelhead) and 10% (Coho Salmon) increase in flows predicted to optimize habitat availability. Thus, small-scale heterogeneity in velocity used by drift-feeding fish can lead to large biases in flow assessments.

Null, S. E., Ligare, S. T., & Viers, J. H. (2013). A Method to Consider Whether Dams Mitigate Climate Change Effects on Stream Temperatures. *Journal of the American Water Resources Association,* 49(6), 1456-1472. https://doi.org/10.1111/jawr.12102

This article provides a method for examining mesoscale water quality objectives downstream of dams with anticipated climate change using a multimodel approach. Coldwater habitat for species such as trout and salmon has been reduced by water regulation, dam building, and land use change that alter stream temperatures. Climate change is an additional threat. Changing hydroclimatic conditions will likely impact water temperatures below dams and affect downstream ecology. We model reservoir thermal dynamics and release operations (assuming that operations remain unchanged through time) of hypothetical reservoirs of different sizes, elevations, and latitudes with climate-forced inflow hydrologies to examine the potential to manage water temperatures for coldwater habitat. All models are one dimensional and operate on a weekly timestep. Results are presented as water temperature change from the historical time period and indicate that reservoirs release water that is cooler than upstream conditions, although the absolute temperatures of reaches below dams warm with climate change. Stream temperatures are sensitive to changes in reservoir volume, elevation, and latitude. Our approach is presented as a proof of concept study to evaluate reservoir regulation effects on stream temperatures and coldwater habitat with climate change.

Ohlberger, J., Buehrens, T. W., Brenkman, S. J., Crain, P., Quinn, T. P., & Hilborn, R. (2018). Effects of past and projected river discharge variability on freshwater production in an anadromous fish. *Freshwater Biology,* 63(4), 331-340. https://doi.org/10.1111/fwb.13070

Knowledge about population responses to environmental variability, including extreme climatic events, is crucial for understanding their current status and likely fate under future environmental change. The frequency and intensity of extreme events is projected to increase, especially in freshwater ecosystems. Anadromous fishes depend on freshwater habitats for spawning and juvenile rearing, making them sensitive to altered hydrologic regimes. Here, we evaluate the effect of past and projected variability in river hydrology on freshwater production of naturally spawning coho salmon populations from coastal river systems in Washington, USA. Using a stage-based life-cycle model, we show that juvenile production during freshwater residence depends on river flow characteristics. Most importantly, juvenile production is reduced by low minimum stream flows during summer. Based on climate model projections suggesting more extreme summer droughts in the region, we then simulate changes in river flow characteristics and quantify the effects of more frequent and severe low flows during summer on juvenile production as well as the harvest that can be sustained in these populations. Our results demonstrate that changes in hydrologic regimes due to environmental change, especially extreme low flows during summer, may significantly affect juvenile production in anadromous fishes such as coho salmon and the services these populations provide to their ecosystems and humans. Understanding population responses to extreme climatic events is thus essential for improving species conservation and risk assessments.

Perry, L. G., Reynolds, L. V., Beechie, T. J., Collins, M. J., & Shafroth, P. B. (2015). Incorporating climate change projections into riparian restoration planning and design. *Ecohydrology,* 8(5), 863-879. https://doi.org/10.1002/eco.1645

Climate change and associated changes in streamflow may alter riparian habitats substantially in coming decades. Riparian restoration provides opportunities to respond proactively to projected climate change effects, increase riparian ecosystem resilience to climate change, and simultaneously address effects of both climate change and other human disturbances. However, climate change may alter which restoration methods are most effective and which restoration goals can be achieved. Incorporating climate change into riparian restoration planning and design is critical to long-term restoration of desired community composition and ecosystem services. In this review, we discuss and provide examples of how climate change might be incorporated into restoration planning at the key stages of assessing the project context, establishing restoration goals and design criteria, evaluating design alternatives, and monitoring restoration outcomes. Restoration planners have access to numerous tools to predict future climate, streamflow, and riparian ecology at restoration sites. Planners can use those predictions to assess which species or ecosystem services will be most vulnerable under future conditions, and which sites will be most suitable for restoration. To accommodate future climate and streamflow change, planners may need to adjust methods for planting, invasive species control, channel and floodplain reconstruction, and water management. Given the considerable uncertainty in future climate and streamflow projections, riparian ecological responses, and effects on restoration outcomes, planners will need to consider multiple potential future scenarios, implement a variety of restoration methods, design projects with flexibility to adjust to future conditions, and plan to respond adaptively to unexpected change.

Prudhomme, C., Wilby, R. L., Crooks, S., Kay, A. L., & Reynard, N. S. (2010). Scenario-neutral approach to climate change impact studies: Application to flood risk. *Journal of Hydrology,* 390(3-4), 198-209. https://doi.org/10.1016/j.jhydrol.2010.06.043

This paper presents a novel framework for undertaking climate change impact studies, which can be used for testing the robustness of precautionary climate change allowances used in engineering design. It is illustrated with respect to fluvial flood risk in the UK. The methodology departs from conventional scenario-led impact studies because it is based on sensitivity analyses of catchment responses to a plausible range of climate changes (rather than the time-varying outcome of individual scenarios), making it scenario-neutral. The method involves separating the climate change projections (the hazard) from the catchment responsiveness (the vulnerability) expressed as changes in peak flows. By combining current understanding of likelihood of the climate change hazard with knowledge of the sensitivity of a given catchment, it is possible to evaluate the fraction of climate model projections that would not be accommodated by specified safety margins. This enables rapid appraisal of existing or new precautionary allowances for a set of climate change projections, but also for any new set of climate change projections for example arising from a new generation of climate models as soon as they are available, or when focusing on a different planning time horizon, without the need for undertaking a new climate change impact analysis with the new scenarios. The approach is demonstrated via an assessment of the UK Government's 20% allowance for climate change applied in two contrasting catchments. In these exemplars, the allowance defends against the majority of sampled climate projections for the 2080s from the IPCC-AR4 GCM and UKCP09 RCM runs but it is still possible to identify a sub-set of regional scenarios that would exceed the 20% threshold.

Puget Sound Partnership. (2017). *Chinook Salmon Projects and Climate Change: Guidance on questions to ask when reveiwing and evaluating restoration and protection projects.* Adaptation International EcoAdapt. Retrieved from http://www.ecoadapt.org/data/library-documents/Lead%20Entity%20Guidance%20Chinook%20and%20Climate%20FINAL%209_6_17.pdf

The Salmon Recovery Funding Board (SRFB) decides how state and federal money supporting salmon recovery will be spent. Although the SRFB does not currently require that project proposal reviewers use climate resiliency guidance or questions to evaluate proposals, they have shown increasing interest in ensuring that watershed- and regional-scale strategies and actions consider the potential impacts of climate change. This document is targeted toward Lead Entities who are seeking support on how to incorporate climate change considerations in the development, evaluation, scoring, and ultimately the prioritization of projects within a watershed.

Pyne, M. I., & Poff, N. L. (2017). Vulnerability of stream community composition and function to projected thermal warming and hydrologic change across ecoregions in the western United States. *Global Change Biology,* 23(1), 77-93. https://doi.org/10.1111/gcb.13437

Shifts in biodiversity and ecological processes in stream ecosystems in response to rapid climate change will depend on how numerically and functionally dominant aquatic insect species respond to changes in stream temperature and hydrology. Across 253 minimally perturbed streams in eight ecoregions in the western USA, we modeled the distribution of 88 individual insect taxa in relation to existing combinations of maximum summer temperature, mean annual streamflow, and their interaction. We used a heat map approach along with downscaled general circulation model (GCM) projections of warming and streamflow change to estimate site-specific extirpation likelihood for each taxon, allowing estimation of whole-community change in streams across these ecoregions. Conservative climate change projections indicate a 30-40% loss of taxa in warmer, drier ecoregions and 10-20% loss in cooler, wetter ecoregions where taxa are relatively buffered from projected warming and hydrologic change. Differential vulnerability of taxa with key functional foraging roles in processing basal resources suggests that climate change has the potential to modify stream trophic structure and function (e.g., alter rates of detrital decomposition and algal consumption), particularly in warmer and drier ecoregions. We show that streamflow change is equally as important as warming in projected risk to stream community composition and that the relative threat posed by these two fundamental drivers varies across ecoregions according to projected gradients of temperature and hydrologic change. Results also suggest that direct human modification of streams through actions such as water abstraction is likely to further exacerbate loss of taxa and ecosystem alteration, especially in drying climates. Management actions to mitigate climate change impacts on stream ecosystems or to proactively adapt to them will require regional calibration, due to geographic variation in insect sensitivity and in exposure to projected thermal warming and hydrologic change.

Robinson, B., & Herman, J. D. (2019). A framework for testing dynamic classification of vulnerable scenarios in ensemble water supply projections. *Climatic Change,* 152(3-4), 431-448. https://doi.org/10.1007/s10584-018-2347-3

Recent water resources planning studies have proposed climate adaptation strategies in which infrastructure and policy actions are triggered by observed thresholds or signposts. However, the success of such strategies depends on whether thresholds can be accurately linked to future vulnerabilities. This study presents a framework for testing the ability of adaptation thresholds to dynamically identify vulnerable scenarios within ensemble projections. Streamflow projections for 91 river sites predominantly in the western USA are used as a case study in which vulnerability is determined by the ensemble members with the lowest 10% of end-of-century mean annual flow. Illustrative planning thresholds are defined through time for each site based on the mean streamflow below which a specified fraction of scenarios is vulnerable. We perform a leave-one-out cross-validation to compute the frequency of incorrectly identifying or failing to identify a vulnerable scenario (false positives and false negatives, respectively). Results show that in general, this method of defining thresholds can identify vulnerable scenarios with low false positive rates (<10%), but with false negative rates for many rivers remaining higher than random chance until roughly 2060. This finding highlights the tradeoff between frequently triggering unnecessary action and failing to identify potential vulnerabilities until later in the century, and suggests room for improvement in the threshold-setting technique that could be benchmarked with this approach. This testing framework could extend to thresholds defined with multivariate statistics, or to any application using thresholds and ensemble projections, such as long-term flood and drought risk, or sea level rise.

Rosero-Lopez, D., Walter, M. T., Flecker, A. S., Lloret, P., De Bievre, B., Gonzalez-Zeas, D., . . . Dangles, O. (2019). Streamlined eco-engineering approach helps define environmental flows for tropical Andean headwaters. *Freshwater Biology,* 64(7), 1315-1325. https://doi.org/10.1111/fwb.13307

Applying the environmental flows concept to human-altered lotic ecosystems continues to face many practical challenges and barriers. Here, we modify a previously proposed framework, the Eco-Engineering Decision Scaling, for application to part of the water supply system of Quito, Ecuador. Specifically, we used feedback from engineers and water managers to develop a common set of metrics for defining flow-ecology relationships and assess managed-flow impacts on stream ecology. At 12 sites over 3 years, we collected flow and benthic invertebrate data (taxonomic richness, taxa important for fish, functional feeding groups, and water quality-sensitive taxa) during wet and dry seasons. We then used these data to identify flow thresholds (relative to unmanaged flows) where flow withdrawal caused visible ecological impacts. For this system, reduction of flow to 20% of the annual median was detrimental to benthic communities, while reductions to 40% of the annual median flow caused a variety of responses in the system. A trade-off analysis of weighted metrics showed that a 50% benthic fauna richness could be sustained if dry season flows were maintained between 28% and 40% of the unmanaged median annual flow. This study provides a roadmap for bridging between eco-engineering theoretical frameworks and the adoption of the environmental flows concept as actionable management thresholds.

Safeeq, M., Mauger, G. S., Grant, G. E., Arismendi, I., Hamlet, A. F., & Lee, S. Y. (2014). Comparing Large-Scale Hydrological Model Predictions with Observed Streamflow in the Pacific Northwest: Effects of Climate and Groundwater. *Journal of Hydrometeorology,* 15(6), 2501-2521. https://doi.org/10.1175/jhm-d-13-0198.1

Assessing uncertainties in hydrologic models can improve accuracy in predicting future streamflow. Here, simulated streamflows using the Variable Infiltration Capacity (VIC) model at coarse (degrees) spatial resolutions were evaluated against observed streamflows from 217 watersheds. In particular, the adequacy of VIC simulations in groundwater- versus runoff-dominated watersheds using a range of flow metrics relevant for water supply and aquatic habitat was examined. These flow metrics were 1) total annual streamflow; 2) total fall, winter, spring, and summer season streamflows; and 3) 5th, 25th, 50th, 75th, and 95th flow percentiles. The effect of climate on model performance was also evaluated by comparing the observed and simulated streamflow sensitivities to temperature and precipitation. Model performance was evaluated using four quantitative statistics: nonparametric rank correlation , normalized Nash-Sutcliffe efficiency NNSE, root-mean-square error RMSE, and percent bias PBIAS. The VIC model captured the sensitivity of streamflow for temperature better than for precipitation and was in poor agreement with the corresponding temperature and precipitation sensitivities derived from observed streamflow. The model was able to capture the hydrologic behavior of the study watersheds with reasonable accuracy. Both total streamflow and flow percentiles, however, are subject to strong systematic model bias. For example, summer streamflows were underpredicted (PBIAS = -13%) in groundwater-dominated watersheds and overpredicted (PBIAS = 48%) in runoff-dominated watersheds. Similarly, the 5th flow percentile was underpredicted (PBIAS = -51%) in groundwater-dominated watersheds and overpredicted (PBIAS = 19%) in runoff-dominated watersheds. These results provide a foundation for improving model parameterization and calibration in ungauged basins.

Singh, R., Wagener, T., Crane, R., Mann, M. E., & Ning, L. (2014). A vulnerability driven approach to identify adverse climate and land use change combinations for critical hydrologic indicator thresholds: Application to a watershed in Pennsylvania, USA. *Water Resources Research,* 50(4), 3409-3427. https://doi.org/10.1002/2013wr014988

Large uncertainties in streamflow projections derived from downscaled climate projections of precipitation and temperature can render such simulations of limited value for decision making in the context of water resources management. New approaches are being sought to provide decision makers with robust information in the face of such large uncertainties. We present an alternative approach that starts with the stakeholder's definition of vulnerable ranges for relevant hydrologic indicators. Then the modeled system is analyzed to assess under what conditions these thresholds are exceeded. The space of possible climates and land use combinations for a watershed is explored to isolate subspaces that lead to vulnerability, while considering model parameter uncertainty in the analysis. We implement this concept using classification and regression trees (CART) that separate the input space of climate and land use change into those combinations that lead to vulnerability and those that do not. We test our method in a Pennsylvania watershed for nine ecological and water resources related streamflow indicators for which an increase in temperature between 3 degrees C and 6 degrees C and change in precipitation between -17% and 19% is projected. Our approach provides several new insights, for example, we show that even small decreases in precipitation (approximate to 5%) combined with temperature increases greater than 2.5 degrees C can push the mean annual runoff into a slightly vulnerable regime. Using this impact and stakeholder driven strategy, we explore the decision-relevant space more fully and provide information to the decision maker even if climate change projections are ambiguous.

Sloat, M. R., Reeves, G. H., & Christiansen, K. R. (2017). Stream network geomorphology mediates predicted vulnerability of anadromous fish habitat to hydrologic change in southeast Alaska. *Global Change Biology,* 23(2), 604-620. https://doi.org/10.1111/gcb.13466

In rivers supporting Pacific salmon in southeast Alaska, USA, regional trends toward a warmer, wetter climate are predicted to increase mid- and late-21st-century mean annual flood size by 17% and 28%, respectively. Increased flood size could alter stream habitats used by Pacific salmon for reproduction, with negative consequences for the substantial economic, cultural, and ecosystem services these fish provide. We combined field measurements and model simulations to estimate the potential influence of future flood disturbance on geomorphic processes controlling the quality and extent of coho, chum, and pink salmon spawning habitat in over 800 southeast Alaska watersheds. Spawning habitat responses varied widely across watersheds and among salmon species. Little variation among watersheds in potential spawning habitat change was explained by predicted increases in mean annual flood size. Watershed response diversity was mediated primarily by topographic controls on stream channel confinement, reach-scale geomorphic associations with spawning habitat preferences, and complexity in the pace and mode of geomorphic channel responses to altered flood size. Potential spawning habitat loss was highest for coho salmon, which spawn over a wide range of geomorphic settings, including steeper, confined stream reaches that are more susceptible to streambed scour during high flows. We estimated that 9-10% and 13-16% of the spawning habitat for coho salmon could be lost by the 2040s and 2080s, respectively, with losses occurring primarily in confined, higher-gradient streams that provide only moderate-quality habitat. Estimated effects were lower for pink and chum salmon, which primarily spawn in unconfined floodplain streams. Our results illustrate the importance of accounting for valley and reach-scale geomorphic features in watershed assessments of climate vulnerability, especially in topographically complex regions. Failure to consider the geomorphic context of stream networks will hamper efforts to understand and mitigate the vulnerability of anadromous fish habitat to climate-induced hydrologic change.

Snover, A. K., Mantua, N. J., Littell, J. S., Alexander, M. A., McClure, M. M., & Nye, J. (2013). Choosing and Using Climate-Change Scenarios for Ecological-Impact Assessments and Conservation Decisions. *Conservation Biology,* 27(6), 1147-1157. https://doi.org/10.1111/cobi.12163

Increased concern over climate change is demonstrated by the many efforts to assess climate effects and develop adaptation strategies. Scientists, resource managers, and decision makers are increasingly expected to use climate information, but they struggle with its uncertainty. With the current proliferation of climate simulations and downscaling methods, scientifically credible strategies for selecting a subset for analysis and decision making are needed. Drawing on a rich literature in climate science and impact assessment and on experience working with natural resource scientists and decision makers, we devised guidelines for choosing climate-change scenarios for ecological impact assessment that recognize irreducible uncertainty in climate projections and address common misconceptions about this uncertainty. This approach involves identifying primary local climate drivers by climate sensitivity of the biological system of interest; determining appropriate sources of information for future changes in those drivers; considering how well processes controlling local climate are spatially resolved; and selecting scenarios based on considering observed emission trends, relative importance of natural climate variability, and risk tolerance and time horizon of the associated decision. The most appropriate scenarios for a particular analysis will not necessarily be the most appropriate for another due to differences in local climate drivers, biophysical linkages to climate, decision characteristics, and how well a model simulates the climate parameters and processes of interest. Given these complexities, we recommend interaction among climate scientists, natural and physical scientists, and decision makers throughout the process of choosing and using climate-change scenarios for ecological impact assessment.

Snyder, C. D., Hitt, N. P., & Young, J. A. (2015). Accounting for groundwater in stream fish thermal habitat responses to climate change. *Ecological Applications,* 25(5), 1397-1419. https://doi.org/10.1890/14-1354.1

Forecasting climate change effects on aquatic fauna and their habitat requires an understanding of how water temperature responds to changing air temperature (i.e., thermal sensitivity). Previous efforts to forecast climate effects on brook trout (Salvelinus fontinalis) habitat have generally assumed uniform air-water temperature relationships over large areas that cannot account for groundwater inputs and other processes that operate at finer spatial scales. We developed regression models that accounted for groundwater influences on thermal sensitivity from measured air-water temperature relationships within forested watersheds in eastern North America (Shenandoah National Park, Virginia, USA, 78 sites in nine watersheds). We used these reach-scale models to forecast climate change effects on stream temperature and brook trout thermal habitat, and compared our results to previous forecasts based upon large-scale models. Observed stream temperatures were generally less sensitive to air temperature than previously assumed, and we attribute this to the moderating effect of shallow groundwater inputs. Predicted groundwater temperatures from air-water regression models corresponded well to observed groundwater temperatures elsewhere in the study area. Predictions of brook trout future habitat loss derived from our fine-grained models were far less pessimistic than those from prior models developed at coarser spatial resolutions. However, our models also revealed spatial variation in thermal sensitivity within and among catchments resulting in a patchy distribution of thermally suitable habitat. Habitat fragmentation due to thermal barriers therefore may have an increasingly important role for trout population viability in headwater streams. Our results demonstrate that simple adjustments to air-water temperature regression models can provide a powerful and cost-effective approach for predicting future stream temperatures while accounting for effects of groundwater.

Sol, S. Y., Hanson, A. C., Marcoe, K., & Johnson, L. L. (2019). Changes in Fish Assemblages at the Mirror Lake Complex in the Lower Columbia River Before and After a Culvert Modification. *North American Journal of Fisheries Management,* 39(6), 1348-1359. https://doi.org/10.1002/nafm.10374

Changes in fish assemblages were examined before and after a culvert was modified to improve the fish passage at the Mirror Lake Complex (MLC), located along the Columbia River Gorge, Oregon. Conditions at the culvert limited water flow between the Columbia River and the MLC during certain portions of the year; thus, the outlet and interior of the culvert were modified to improve fish passage. Prior to the culvert modification, three sites were sampled monthly between April and August 2008, 5.0 km and 0.5 km upstream of the culvert and immediately downstream of the culvert. Following the culvert modification in the late summer of 2008, the same sites were sampled from 2009 to 2012, with two additional sites added in 2010. Prior to the culvert modification, the lower sites (i.e., the sites closest to the Columbia River) supported native and nonnative fish species, while the upper sites were dominated by native species. During the 4 years of monitoring after culvert modification, these distinctions between the upper and lower sites remained. A significant increase in water temperature and species richness was observed at the site just upstream of the culvert, but other changes in fish composition (density, diversity, percent of nonnative species) were not observed. However, at the upper sites, while nonnative species were absent before culvert modification, they were present after modification. Modifications made at the culvert, in combination with seasonal variation in water level and water temperature, may have influenced fish communities in the MLC. Given predicted regional and global climatic changes, our study indicates the importance of long-term monitoring of restoration sites for the presence of nonnative species and the effects of environmental variables, such as water temperature.

Stakhiv, E. Z. (2011). Pragmatic Approaches for Water Management Under Climate Change Uncertainty. *Journal of the American Water Resources Association,* 47(6), 1183-1196. https://doi.org/10.1111/j.1752-1688.2011.00589.x

Water resources management is in a difficult transition phase, trying to accommodate large uncertainties associated with climate change while struggling to implement a difficult set of principles and institutional changes associated with integrated water resources management. Water management is the principal medium through which projected impacts of global warming will be felt and ameliorated. Many standard hydrological practices, based on assumptions of a stationary climate, can be extended to accommodate numerous aspects of climate uncertainty. Classical engineering risk and reliability strategies developed by the water management profession to cope with contemporary climate uncertainties can also be effectively employed during this transition period, while a new family of hydrological tools and better climate change models are developed. An expansion of the concept of "robust decision making,'' coupled with existing analytical tools and techniques, is the basis for a new approach advocated for planning and designing water resources infrastructure under climate uncertainty. Ultimately, it is not the tools and methods that need to be revamped as much as the suite of decision rules and evaluation principles used for project justification. They need to be aligned to be more compatible with the implications of a highly uncertain future climate trajectory, so that the hydrologic effects of that uncertainty are correctly reflected in the design of water infrastructure.

Strauch, R. L., Raymond, C. L., Rochefort, R. M., Hamlet, A. F., & Lauver, C. (2015). Adapting transportation to climate change on federal lands in Washington State, USA. *Climatic Change,* 130(2), 185-199. https://doi.org/10.1007/s10584-015-1357-7

Research scientists collaborated with federal land managers of two national parks and two national forests to conduct a climate change vulnerability assessment and to identify adaptation strategies for a transportation network covering 28,900 km of roads and trails in north-central Washington, U.S.A. The assessment employed observations of sensitivity and response to climatic variability, downscaled climate projections, literature reviews, current management policies and practices, expert knowledge, and stakeholder engagement. Primary pathways for climate impacts focused on projected increases in extreme high flows and flooding, elevated winter soil moisture and landslide hazards, and loss of snowpack. The biggest impacts to roads and trails are expected from temperature-induced changes in hydrologic regimes that enhance autumn flooding and reduce spring snowpack. Projected higher winter soil moisture caused by changes in seasonal precipitation and snow accumulation could reduce slope stability. Earlier snowmelt may lengthen the snow-free season for visitor use and agency operations. Infrastructure age, design, maintenance, location, use, and limited redundancy along with funding policies and management, influence the sensitivities of the transportation system. Vulnerabilities were identified based on when and where these sensitivities to changes in climate may emerge. Adaptation strategies and tactics identified to address these vulnerabilities included: upgrading stream crossing and drainage design, changing use and maintenance, relocating or closing roads and trails, modifying funding policies, and expanding pubic engagement. Many adaptation options are "no regrets" approaches to changes in climate projected for the 2040s and 2080s that can be applied to other resource sectors and mountainous regions.

Surfleet, C. G., & Tullos, D. (2013). Uncertainty in hydrologic modelling for estimating hydrologic response due to climate change (Santiam River, Oregon). *Hydrological Processes,* 27(25), 3560-3576. https://doi.org/10.1002/hyp.9485

This paper explores the predicted hydrologic responses associated with the compounded error of cascading global circulation model (GCM) uncertainty through hydrologic model uncertainty due to climate change. A coupled groundwater and surface water flow model (GSFLOW) was used within the differential evolution adaptive metropolis (DREAM) uncertainty approach and combined with eight GCMs to investigate uncertainties in hydrologic predictions for three subbasins of varying hydrogeology within the Santiam River basin in Oregon, USA. Predictions of future hydrology in the Santiam River include increases in runoff in the fall and winter months and decreases in runoff for the spring and summer months. One-year peak flows were predicted to increase whereas 100-year peak flows were predicted to slightly decrease. The predicted 10-year 7-day low flow decreased in two subbasins with little groundwater influences but increased in another subbasin with substantial groundwater influences. Uncertainty in GCMs represented the majority of uncertainty in the analysis, accounting for an average deviation from the median of 66%. The uncertainty associated with use of GSFLOW produced only an 8% increase in the overall uncertainty of predicted responses compared to GCM uncertainty. This analysis demonstrates the value and limitations of cascading uncertainty from GCM use through uncertainty in the hydrologic model, offers insight into the interpretation and use of uncertainty estimates in water resources analysis, and illustrates the need for a fully nonstationary approach with respect to calibrating hydrologic models and transferring parameters across basins and time for climate change analyses.

Thompson, L. C., Escobar, M. I., Mosser, C. M., Purkey, D. R., Yates, D., & Moyle, P. B. (2012). Water Management Adaptations to Prevent Loss of Spring-Run Chinook Salmon in California under Climate Change. *Journal of Water Resources Planning and Management,* 138(5), 465-478. https://doi.org/10.1061/(asce)wr.1943-5452.0000194

Spring-run Chinook salmon (Oncorhynchus tshawytscha) are particularly vulnerable to climate change because adults over-summer in freshwater streams before spawning in autumn. We examined streamflow and water temperature regimes that could lead to long-term reductions in spring-run Chinook salmon (SRCS) in a California stream and evaluated management adaptations to ameliorate these impacts. Bias-corrected and spatially downscaled climate data from six general circulation models and two emission scenarios for the period 2010-2099 were used as input to two linked models: a water evaluation and planning (WEAP) model to simulate weekly mean streamflow and water temperature in Butte Creek, California that were used as input to SALMOD, a spatially explicit and size/stage structured model of salmon population dynamics in freshwater systems. For all climate scenarios and model combinations, WEAP yielded lower summer base flows and higher water temperatures relative to historical conditions, while SALMOD yielded increased adult summer thermal mortality and population declines. Of management adaptations tested, only ceasing water diversion for power production from the summer holding reach resulted in cooler water temperatures, more adults surviving to spawn, and extended population survival time, albeit with a significant loss of power production. The most important conclusion of this work is that long-term survival of SRCS in Butte Creek is unlikely in the face of climate change and that simple changes to water operations are not likely to dramatically change vulnerability to extinction.

Timpane-Padgham, B. L., Beechie, T., & Klinger, T. (2017). A systematic review of ecological attributes that confer resilience to climate change in environmental restoration. *Plos One,* 12(3). https://doi.org/10.1371/journal.pone.0173812

Ecological restoration is widely practiced as a means of rehabilitating ecosystems and habitats that have been degraded or impaired through human use or other causes. Restoration practices now are confronted by climate change, which has the potential to influence long-term restoration outcomes. Concepts and attributes from the resilience literature can help improve restoration and monitoring efforts under changing climate conditions. We systematically examined the published literature on ecological resilience to identify biological, chemical, and physical attributes that confer resilience to climate change. We identified 45 attributes explicitly related to climate change and classified them as individual-(9), population-(6), community-(7), ecosystem-(7), or process-level attributes (16). Individual studies defined resilience as resistance to change or recovery from disturbance, and only a few studies explicitly included both concepts in their definition of resilience. We found that individual and population attributes generally are suited to species-or habitat-specific restoration actions and applicable at the population scale. Community attributes are better suited to habitat-specific restoration at the site scale, or system-wide restoration at the ecosystem scale. Ecosystem and process attributes vary considerably in their type and applicability. We summarize these relationships in a decision support table and provide three example applications to illustrate how these classifications can be used to prioritize climate change resilience attributes for specific restoration actions. We suggest that (1) including resilience as an explicit planning objective could increase the success of restoration projects, (2) considering the ecological context and focal scale of a restoration action is essential in choosing appropriate resilience attributes, and (3) certain ecological attributes, such as diversity and connectivity, are more commonly considered to confer resilience because they apply to a wide variety of species and ecosystems. We propose that identifying sources of ecological resilience is a critical step in restoring ecosystems in a changing climate.

Tohver, I. M., Hamlet, A. F., & Lee, S. Y. (2014). Impacts of 21st-Century Climate Change on Hydrologic Extremes in the Pacific Northwest Region of North America. *Journal of the American Water Resources Association,* 50(6), 1461-1476. https://doi.org/10.1111/jawr.12199

Climate change projections for the Pacific Northwest (PNW) region of North America include warmer temperatures (T), reduced precipitation (P) in summer months, and increased P during all other seasons. Using a physically based hydrologic model and an ensemble of statistically downscaled global climate model scenarios produced by the Columbia Basin Climate Change Scenarios Project, we examine the nature of changing hydrologic extremes (floods and low flows) under natural conditions for about 300 river locations in the PNW. The combination of warming, and shifts in seasonal P regimes, results in increased flooding and more intense low flows for most of the basins in the PNW. Flood responses depend on average midwinter T and basin type. Mixed rain and snow basins, with average winter temperatures near freezing, typically show the largest increases in flood risk because of the combined effects of warming (increasing contributing basin area) and more winter P. Decreases in low flows are driven by loss of snowpack, drier summers, and increasing evapotranspiration in the simulations. Energy-limited basins on the west side of the Cascades show the strongest declines in low flows, whereas more arid, water-limited basins on the east side of the Cascades show smaller reductions in low flows. A fine-scale analysis of hydrologic extremes over the Olympic Peninsula echoes the results for the larger rivers discussed above, but provides additional detail about topographic gradients.

Trudel, M., Doucet-Genereux, P. L., Leconte, R., & Cote, B. (2016). Vulnerability of Water Demand and Aquatic Habitat in the Context of Climate Change and Analysis of a No-Regrets Adaptation Strategy: Study of the Yamaska River Basin, Canada. *Journal of Hydrologic Engineering,* 21(2). https://doi.org/10.1061/(asce)he.1943-5584.0001298

Climate change will have a significant impact on the hydrological cycle. This paper presents the results of a pilot project for the Yamaska River in Quebec. The objective of this project is to evaluate the river's vulnerability to low flows attributable to climate change and to analyze a no-regrets adaptation strategy at locations identified as vulnerable. The vulnerability was evaluated using statistical indicators (low flow indices) based on long-term observations at four locations in the basin. A distributed physically-based hydrological model in use in Quebec was calibrated and validated against observed streamflow data to properly represent low flows. Hydrological simulations used seven climate projections provided by the north american regional climate change assessment program (NARCCAP) s project. Also, five members of the canadian regional climate model (CRCM), nested with the coupled global climate model (CGCM) under the special report on emission scenarios (SRES) A2 emission scenario, were run for a reference

(1971-2000) period and a future (2041-2070) period. Streamflow simulations indicate a degradation of future low flow conditions, particularly in June and August, when compared to the reference period. In addition, the 7-day low flow value with a 2-year return period (7Q2) and the 7-day low flow value with a 10-year return period (7Q10) decrease by 16-64% and 18-45% respectively. A no-regrets adaptation strategy allowing stakeholders to reduce withdrawal according to alert levels was implemented. Simulations of the application of the no-regrets adaptation strategy reduced the number of days where streamflows are below the Crisis level in the future period by at least 20%.

Turner, S. W. D., Blackwell, R. J., Smith, M. A., & Jeffrey, P. J. (2016). Risk-based water resources planning in England and Wales: challenges in execution and implementation. *Urban Water Journal,* 13(2), 182-197. https://doi.org/10.1080/1573062x.2014.955856

In this paper we describe the execution of a risk-based analysis on a simple, small-scale water resources planning problem. We aim to understand whether a risk-based approach could underpin the regulated water resources planning process in England and Wales. We demonstrate the practical feasibility of the approach and identify clear benefits over the conventional planning methods. We also identify several nontrivial challenges for scaling up and caution against the view that better quality decisions would emerge naturally from risk-based analyses. Useful future research might focus on: (1) the development of practical methodologies for applying these approaches to larger, more complex resource zones; (2) identifying and overcoming problems associated with regulating a risk-based water resources planning process; and (3) developing methods of economic options appraisal that can deploy the outputs of a risk-based analysis to inform planning decisions.

Underwood, B. S., Mascaro, G., Chester, M. V., Fraser, A., Lopez-Cantu, T., & Samaras, C. (2020). Past and Present Design Practices and Uncertainty in Climate Projections are Challenges for Designing Infrastructure to Future Conditions. *Journal of Infrastructure Systems,* 26(3). https://doi.org/10.1061/(asce)is.1943-555x.0000567

Designing infrastructure for a changing climate remains a major challenge for engineers. In popular discourse a narrative has emerged that infrastructures are likely underdesigned for the future. Weather-related hazards are directly embedded in the infrastructure design process. Yet the codes and standards that engineers use for this risk analysis have been changing for decades, sometimes increasing and other times decreasing design values. Further complicating the issue is that climate projections show increasing or decreasing intensities depending on the hazard and region. Thus, it is not clear that infrastructure is universally underdesigned. Here, analyses are developed at both regional and national scales using precipitation and roadway drainage systems to answer this question. First, it is shown that modeling uncertainty can pose challenges for using future projections to update region-specific standards. Second, the results show that depending on the historical design conditions and the direction of projections, roadway drainage infrastructures may be designed appropriately in some regions while in others they are possibly underdesigned. Given these uncertainties, the authors believe that there is a need for alternative design paradigms, and these needs are discussed.

Vano, J. A., Arnold, J. R., Nijssen, B., Clark, M. P., Wood, A. W., Gutmann, E. D., . . . Lehner, F. (2018). DOs and DON'Ts for using climate change information for water resource planning and management:

guidelines for study design. *Climate Services,* 12, 1-13. https://doi.org/10.1016/j.cliser.2018.07.002

Water managers are actively incorporating climate change information into their long- and short-term planning processes. This is generally seen as a step in the right direction because it supplements traditional methods, providing new insights that can help in planning for a non-stationary climate. However, the continuous evolution of climate change information can make it challenging to use available information appropriately. Advice on how to use the information is not always straightforward and typically requires extended dialogue between information producers and users, which is not always feasible. To help navigate better the ever-changing climate science landscape, this review is organized as a set of nine guidelines for water managers and planners that highlight better practices for incorporating climate change information into water resource planning and management. Each DOs and DON'Ts recommendation is given with context on why certain strategies are preferable and addresses frequently asked questions by exploring past studies and documents that provide guidance, including real-world examples mainly, though not exclusively, from the United States. This paper is intended to provide a foundation that can expand through continued dialogue within and between the climate science and application communities worldwide, a two-way information sharing that can increase the actionable nature of the information produced and promote greater utility and appropriate use.

Wasko, C., Westra, S., Nathan, R., Orr, H. G., Villarini, G., Villalobos Herrera, R., & Fowler, H. J. (2021). Incorporating climate change in flood estimation guidance. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 379(2195), 20190548. https://doi.org/10.1098/rsta.2019.0548

Research into potential implications of climate change on flood hazard has made significant progress over the past decade, yet efforts to translate this research into practical guidance for flood estimation remain in their infancy. In this commentary, we address the question: how best can practical flood guidance be modified to incorporate the additional uncertainty due to climate change? We begin by summarizing the physical causes of changes in flooding and then discuss common methods of design flood estimation in the context of uncertainty. We find that although climate science operates across aleatory, epistemic and deep uncertainty, engineering practitioners generally only address aleatory uncertainty associated with natural variability through standards-based approaches. A review of existing literature and flood guidance reveals that although research efforts in hydrology do not always reflect the methods used in flood estimation, significant progress has been made with many jurisdictions around the world now incorporating climate change in their flood guidance. We conclude that the deep uncertainty that climate change brings signals a need to shift towards more flexible design and planning approaches, and future research effort should focus on providing information that supports the range of flood estimation methods used in practice.

Wenger, S. J., Luce, C. H., Hamlet, A. F., Isaak, D. J., & Neville, H. M. (2010). Macroscale hydrologic modeling of ecologically relevant flow metrics. *Water Resources Research,* 46. https://doi.org/10.1029/2009wr008839

Stream hydrology strongly affects the structure of aquatic communities. Changes to air temperature and precipitation driven by increased greenhouse gas concentrations are shifting timing and volume of streamflows potentially affecting these communities. The variable infiltration capacity (VIC) macroscale hydrologic model has been employed at regional scales to describe and forecast hydrologic changes but has been calibrated and applied mainly to large rivers. An important question is how well VIC runoff simulations serve to answer questions about hydrologic changes in smaller streams, which are important habitat for many fish species. To answer this question, we aggregated gridded VIC outputs within the drainage basins of 55 streamflow gages in the Pacific Northwest United States and compared modeled hydrographs and summary metrics to observations. For most streams, several ecologically relevant aspects of the hydrologic regime were accurately modeled, including center of flow timing, mean annual and summer flows and frequency of winter floods. Frequencies of high and low flows in the summer were not well predicted, however. Predictions were worse for sites with strong groundwater influence, and some sites showed errors that may result from limitations in the forcing climate data. Higher resolution (1/16th degree) modeling provided small improvements over lower resolution (1/8th degree). Despite some limitations, the VIC model appears capable of representing several ecologically relevant hydrologic characteristics in streams, making it a useful tool for understanding the effects of hydrology in delimiting species distributions and predicting the potential effects of climate shifts on aquatic organisms.

Whipple, A. A., & Viers, J. H. (2019). Coupling landscapes and river flows to restore highly modified rivers. *Water Resources Research,* 55(6), 4512-4532. https://doi.org/10.1029/2018wr022783

Modifications to landscapes and flow regimes of rivers have altered the function, biodiversity, and productivity of freshwater ecosystems globally. Reestablishing geomorphological and hydrological conditions necessary to sustain ecosystems is a central challenge for restoration within highly altered systems. Meeting this challenge requires simultaneously addressing multiple and interacting stressors within the context of irreversible changes and socio-economic constraints. Traditionally, river restoration approaches either physically change the landscape or channel (channel-floodplain manipulation) or adjust hydrology (environmental flows), and such actions are often independent. We juxtapose these two subfields of river restoration, which have undergone parallel transformations, from goals of reproducing static representations of form and flow regime to goals of reestablishing processes. The parallel transformations have generated shared ideas, which point to benefits of coupling channel-floodplain manipulation and environmental flow actions to achieve process-based goals. Such coupling supports comprehensive river restoration efforts aimed at supporting resilient ecosystems within human dominated landscapes in a nonstationary climate. We identify four elements of coupled approaches for restoring highly modified rivers: (1) identify physical and ecological process potential given interactive effects of altered landscapes and flows; (2) consider capacity for sustaining identified processes under potential future change; (3) model alternatives for coupled restoration actions to support identified processes; and (4) evaluate alternatives using metrics representing integrative effects of coupled actions. We suggest these emergent elements contribute to the development of standard practices for restoring highly modified rivers and encourage an increasing number and quality of coupled applications. Plain Language Summary Freshwater ecosystems globally have been fundamentally altered and degraded by multiple human modifications of rivers, which have affected the amount and timing of water availability as well as the riverine landscape with which river flows interact. Knowing that it is often impossible or infeasible to completely reverse these impacts, a central challenge for restoring freshwater ecosystems of highly modified rivers is to determine what water management changes and physical habitat restoration actions can be taken to reestablish processes necessary to support ecosystems. These different river restoration approaches have traditionally been considered independently of one another. However, both river restoration subfields have shifted in recent decades from goals of reproducing static representations of channel forms or reference flow regimes to those of

reestablishing processes driven by flow-landscape interaction. This shared understanding points to the benefits of coupling channel-floodplain manipulation and water management for a combined added positive impact to ecosystems. Four elements of coupled approaches are identified: (1) identify process potential; (2) consider capacity under potential future change; (3) model alternatives; and (4) evaluate metrics of integrative effects. This commentary supports the development of standard practices for coupled approaches for restoring highly modified rivers.

Wilhere, G., Atha, J., Quinn, T., Helbrecht, L., & Tohver, I. (2017). *Incorporating Climate Change into the Design of Water Crossing Structures: Final Project Report*. Retrieved from https://wdfw.wa.gov/publications/01867

The following report describes a study conducted by the Washington Department of Fish and Wildlife (WDFW or the Department) from 2014 to 2016. The study represents the Department's initial attempt to explore climate-related changes to stream channel morphology with the intent of determining how climate change could be incorporated into the design of water crossing structures. The Department received a grant from the North Pacific Landscape Conservation Cooperative (NPLCC) that provided essential support for this work. This report fulfills a required deliverable of that grant.

World Bank. (2020). *Resilient Water Infrastructure Design Brief.* Washington, DC. Retrieved from http://hdl.handle.net/10986/34448

The purpose of the Resilient Water Infrastructure Design Brief is to guide users on how resilience can be built into the engineering design of their project. With a focus on the three natural hazards most likely to affect water and sanitation infrastructure (droughts, floods, and high winds from storms), the document provides a six-step process to help users address weather and climate related challenges that are most likely to affect an infrastructure component at some point in its operational lifetime. In order to achieve both systems level resilience and infrastructure level resilience, this design brief should be used in tandem with other World Bank publications, such as the 2018 guidance document "Building the Resilience of WSS Utilities to Climate Change and Other Threats: A Road Map," which emphasizes systems level resilience and analysis. The design brief highlights the relationship between these two documents and the unique function that each serves in improving overall resilience in the water sector. It also includes guidance for users to incorporate resilience design principles into projects' appraisal documents and a sample module/task description for applying the two documents to an engineering design or feasibility study terms of reference.

Wu, H., Kimball, J. S., Elsner, M. M., Mantua, N., Adler, R. F., & Stanford, J. (2012). Projected climate change impacts on the hydrology and temperature of Pacific Northwest rivers. *Water Resources Research,* 48. https://doi.org/10.1029/2012wr012082

A dominant river-tracing-based streamflow and temperature (DRTT) model was developed by coupling stream thermal dynamics with a source-sink routing model. The DRTT model was applied using 1/16 degree (similar to 6 km) resolution gridded daily surface meteorology inputs over a similar to 988,000 km(2) Pacific Northwest (PNW) domain to produce regional daily streamflow and temperature simulations from 1996 to 2005. The DRTT results showed favorable performance for simulation of daily stream temperature (mean R-2 = 0.72 and root-mean-square error = 2.35 degrees C) and discharge

(mean R-2 = 0.52 and annual relative error 14%) against observations from 12 PNW streams. The DRTT was then applied with a macroscale hydrologic model to predict streamflow and temperature changes under historical (1980s) and future (2020s, 2040s, and 2080s) climate change scenarios (IPCC AR4) as they may affect current and future patterns of freshwater salmon habitat and associated productivity of PNW streams. The model projected a 3.5% decrease in mean annual streamflow for the 2020s and 0.6% and 5.5% increases for the 2040s and 2080s, respectively, with projected increase in mean annual stream temperatures from 0.55 degrees C (2020s) to 1.68 degrees C (2080s). However, summer streamflow decreased from 19.3% (2020s) to 30.3% (2080s), while mean summer stream temperatures warmed from 0.92 degrees C to 2.10 degrees C. The simulations indicate that projected climate change will have greater impacts on snow dominant streams, with lower summer streamflows and warmer summer stream temperature changes relative to transient and rain dominant regimes. Lower summer flows combined with warmer stream temperatures suggest a future with widespread increased summertime thermal stress for coldwater fish in the PNW region.

Yan, L., Xiong, L. H., Guo, S. L., Xu, C. Y., Xia, J., & Du, T. (2017). Comparison of four nonstationary hydrologic design methods for changing environment. *Journal of Hydrology,* 551, 132-150. https://doi.org/10.1016/j.jhydrol.2017.06.001

The hydrologic design of nonstationary flood extremes is an emerging field that is essential for water resources management and hydrologic engineering design to cope with changing environment. This paper aims to investigate and compare the capability of four nonstationary hydrologic design strategies, including the expected number of exceedances (ENE), design life level (DLL), equivalent reliability (ER), and average design life level (ADLL), with the last three methods taking into consideration the design life of the project. The confidence intervals of the calculated design floods were also estimated using the non stationary bootstrap approach. A comparison of these four methods was performed using the annual maximum flood series (AMFS) of the Weihe River basin, Jinghe River basin, and Assunpink Creek basin. The results indicated that ENE, ER and ADLL yielded the same or very similar design values and confidence intervals for both increasing and decreasing trends of AMFS considered. DLL also yields similar design values if the relationship between DLL and ER/ADLL return periods is considered. Both ER and ADLL are recommended for practical use as they have associated design floods with the design life period of projects and yield reasonable design quantiles and confidence intervals. Furthermore, by assuming that the design results using either a stationary or nonstationary hydrologic design strategy, should have the same reliability, the ER method enables us to solve the nonstationary hydrologic design problems by adopting the stationary design reliability, thus bridging the gap between stationary and nonstationary design criteria.

Yan, L., Xiong, L. H., Luan, Q. H., Jiang, C., Yu, K. X., & Xu, C. Y. (2020). On the Applicability of the Expected Waiting Time Method in Nonstationary Flood Design. *Water Resources Management,* 34(8), 2585-2601. https://doi.org/10.1007/s11269-020-02581-w

Given a changing environment, estimating a flood magnitude corresponding to a desired return period considering nonstationarity is crucial for hydrological engineering designs. Four nonstationary design methods, namely expected waiting time (EWT), expected number of exceedances (ENE), equivalent reliability (ER), and average design life level (ADLL) have already been proposed in recent years. Among them, the EWT method needs to estimate design flood magnitudes by solving numerically. In addition, EWT requires estimating design quantiles for infinite lifespan, or extrapolation time (t(extra)), to guarantee the convergence of the EWT solution under certain conditions. However, few studies have systematically evaluated pros and cons of the EWT method as to how to determine the t(extra) and what kinds of misunderstandings on the applicability of the EWT method exist. In this study, we aim to provide the first investigation of various factors that influence the value of t(extra) in the EWT method, and provide comprehensive comparison of the four methods from the perspectives of t(extra), design values and associated uncertainties. The annual maximum flood series (AMFS) of 25 hydrological stations, with increasing and decreasing trends, in Pearl River and Weihe River were chosen for illustrations. The results indicate that: (1) the t(extra) of EWT is considerably affected by the trend of AMFS and the choice of extreme distributions. In other words, the t(extra) of stations with increasing trends was significantly smaller than that of stations with decreasing trends, and the t(extra) was also larger for distributions with heavier tail; (2) EWT produced larger design values than ENE for increasing trends, and both EWT and ENE yielded larger design values than ER and ADLL for higher return periods, while complete opposite results were obtained for decreasing trends.

Yigzaw, W., Hossain, F., & Kalyanapu, A. (2013). Impact of Artificial Reservoir Size and Land Use/Land Cover Patterns on Probable Maximum Precipitation and Flood: Case of Folsom Dam on the American River. *Journal of Hydrologic Engineering,* 18(9), 1180-1190. https://doi.org/10.1061/(asce)he.1943-5584.0000722

The design of the dams usually considers available historical data for analysis of the flood frequency. The limitation of this approach is the potential shift in flood frequency due to physically plausible factors that cannot be foreseen during design. For example, future flood extremes may change, among other factors, due to strong local atmospheric feedbacks from the reservoir and surrounding land use and land cover (LULC). Probable maximum flood (PMF), which is the key design parameter for hydraulic features of a dam, is estimated from probable maximum precipitation (PMP) and the hydrology of the watershed. Given the nonlinearity of the rainfall-runoff process, a key question that needs to be answered is How do reservoir size and/or LULC modify extreme flood patterns, specifically probable maximum flood via climatic modification of PMP? Using the American River Watershed (ARW) as a representative example of an impounded watershed with a large artificial reservoir (i.e.,Folsom Dam), this study applied the distributed variable infiltration capacity (VIC) model to simulate the PMF from the atmospheric feedbacks simulated for various LULC scenarios (predam, current scenario, nonirrigation, and reservoir-double). The atmospheric feedbacks were simulated numerically as PMP using the regional atmospheric modeling system (RAMS). The RAMS-generated PMP scenarios were propagated through the VIC model to simulate the PMFs. Comparison of PMF results for predam and current scenario conditions showed that PMF peak flow can decrease by about , while comparison of current scenario with nonirrigation PMF results showed that irrigation development has increased the PMF by . On the other hand, the reservoir size had virtually no detectable impact on PMP and consequently on PMF results. Where downstream levee capacity is already underdesigned to handle a dam's spillway capacity, such as for the case study, such increases indicate a likely impact on downstream flood risk to which any flood management protocol must adapt. The premise that modern dam design and operations should consider an integrated atmospheric-hydrologic modeling approach for estimating proactively potential extreme precipitation variation due to dam-driven LULC change is well-supported by this case study.