FINAL NPLCC PROGRESS REPORT:
An Applied Case Study to Integrate Climate Change into the Design of Water Crossing Structures
NPLCC Agreement #: F14AC00554
Washington Department of Fish and Wildlife
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Table of Contents

Introduction

This document serves as WDFW's final progress report for the project listed above: "An applied case study to integrate climate change into the design of water crossing structures". We have organized this report according the topics listed on the NPLCC Progress Reporting guide, and provided a brief summary for each of the requested topics. A full description of the project methodology and results, and all references, are available in Appendix A. Additional supporting documentation can be found in Appendices B and C.

1. Administrative Information

Project Title	An applied case study to integrate climate change into the design and permitting of water crossing structures.
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2. Public Summary (300 words or less)

In 2014, WDFW began a two-year project to incorporate climate change data into the water crossing design guidance and permitting process. The agency was particularly interested in this work because of its central role in designing and permitting water crossing structures (i.e., culverts and bridges) that provide unimpeded fish passage. Current design guidance does not consider changes in hydrology expected with climate change, in spite of the fact that most water crossing structures are expected to have a 50 to 100 year service life.

WDFW teamed with the Climate Impacts Group at the University of Washington to translate downscaled hydrologic projections for two time periods (2040s and 2080s) into stream channel bankfull width (BFW). BFW is the primary parameter used by WDFW engineers and many others to size culverts. The results of this analysis are spatially explicit projections which show that by the 2040s BFW is likely to increase for many rivers and streams in Washington, and, that culverts designed using only current BFW may be undersized for fish passage under future conditions. Our project also included approaches for helping managers understand how to apply these BFW projections in the context of the inherent uncertainty in climate models. We offer a framework for weighing the risks of not considering future BFW changes, against the costs of designing culverts to accommodate likely, but still uncertain, increases in BFW.

WDFW is working with agency managers to apply these "climate adapted" culvert design guidelines on agency owned lands. We are also working with restoration project proponents in the Chehalis River watershed to use our projections of future BFW for the design of new culverts that will replace existing fish passage barriers. Future work, depending on funding availability, will include creating a web interface for these results making it easier for users to access.

2. Executive Summary

A recently completed project led by the Washington Department of Fish and Wildlife (WDFW) has helped the agency take a significant step towards integrating climate change into the design of water crossing structures. The agency was particularly interested in this project because of its central role in designing and permitting water crossing structures for fish passage. Current design guidance does not consider future changes in stream flows and channel morphology expected to occur with climate change, in spite of the fact that most culverts are typically designed for a 50 to 100 year service life.

Methods and Approach

WDFW teamed with the Climate Impacts Group (CIG) at the University of Washington to translate downscaled hydrologic projections for watersheds across the state into stream channel bankfull width, which is the primary parameter used by WDFW engineers and others to size culverts. Our analysis was comprised of four major steps. The first two steps, conducted by CIG, produced downscaled projections of future temperature and precipitation from 10 global climate models (GCMs), and mean daily flows for 5,270 uniformly distributed grid cells throughout Washington State using a hydrological model that relies on spatially-explicit climate projections as inputs.

The next two steps, which WDFW conducted, estimated bankfull flows from the mean daily flows for each grid cell, and bankfull widths from the bankfull flows. Although 100-year flood flows (Q_{100}) are thought to be accommodated by culvert designs based on BFW, we also report on the percent change in 100-year flood volumes because percent changes in BFW and Q_{100} did not vary in a consistent way. We used CIG's mean daily flow projections from the 10 GCMs to generate projections for 100-year flood volumes. We then calculated percent change between the historical estimate and the mean of the 10 projected future 100-year flood volumes for each grid cell during the 2040s and 2080s time periods.

Results - Projected Changes in Bankfull Width and the 100 Year Flood

The mean BFW is projected to increase in about 80% of grid cells in both time periods. For the 2040s and 2080s, the mean projected changes in BFW are 4.5% and 7.2%, respectively. Projected changes in BFW by grid cell varied by elevation, with the largest changes occurring in high elevation grid cells with mixed rain and snow dominant hydrographs. The largest increase in percent change in bankfull width is projected to occur in the North Cascades Ecoregion (27.0% for the 2040s and 43.5% for the 2080s) and the largest decrease in percent change in bankfull width is projected to occur in the Columbia Basin (-14.8% for the 2040s and -20.7% for the 2080s).

The mean projected percent change in the 100-year flood volume (Q_{100}) is 8.0% for the 2040s and 16.5% for the 2080s. In the 2080s, the range of percent change across all grid cells is from -55 to 180%, with the biggest increases in Q_{100} projected to occur at higher elevations. The mean projected percent change for both BFW and Q_{100} for the 2040s and 2080s time periods shows distinct regional variation. For the 2080s, 2% of grid cells, mostly in the North Cascades Ecoregion, are projected to have a Q_{100} over twice as large as their historical Q_{100}. In contrast, most of the Columbia Basin is projected to have reduced BFW and Q_{100}. According to our projections for the 2080s, 35% of grid cells (over one-third of Washington) will have at least a 25% increase in Q_{100}.

Addressing Uncertainty and Risk

This project also developed approaches for helping managers understand how to apply results in the context of the inherent uncertainty in climate models. We offer a framework for weighing the risks of not considering future peak flow projections, against the costs of designing culverts to accommodate likely, but still uncertain, increases in peak flow. Risk is often thought of as two separate components: probability and cost, or in other words, the likelihood (probability) that an adverse impact (cost) will occur. We could not estimate the likelihood of culvert failure under future climate conditions, nor could we estimate the adverse impacts due to culvert failure, but we did have projections of future conditions that could be used as surrogates. We suggest that the ratio of future to historical bankfull width can be a surrogate for cost - if a culvert built using today's bankfull width is too narrow to accommodate future bankfull flow, then we expect that culvert's future functioning to degrade, implying future potential cost, i.e., harm to fish populations. Our surrogate for probability is the proportion of models that project an increase in future bankfull width.

Future Work
WDFW is working with agency managers to apply these "climate adapted" projections on projects on our own lands. We are also working with restoration project proponents in the Chehalis River watershed to use our projections of future bankfull width for the design of new culverts to replace existing fish passage barriers. Future work, depending on funding availability, will include creating a web interface for these data to make it easier for users to access and navigate.

This report and the projections of future percent change in bankfull width are important potential additions to the water crossing design guidelines provided by WDFW. To avoid future damages to fish movement, fish habitat, and public infrastructure we believe that incorporating projected future changes in bankfull width into culvert design should be standard practice.

4. Purpose and Objectives

The primary purpose of this project was to incorporate climate change projections into the WDFW water crossing design guidance and permitting process. A secondary objective was to explore decision pathways in the culvert design process, in order to develop guidance regarding how and when climate data could be most effectively used by managers.

Our project delivers on both of these objectives. Project results include hydrologic projections derived from downscaled climate projections into the key parameter used by WDFW engineers and others in the design of fish passage structures. Furthermore, the project outlines approaches for managers to use this information in the context of the inherent uncertainty of future climate projections. We present the results in ways which allow users to evaluate both the relative certainty (as defined by model agreement), as well as the magnitude of the change (defined as the mean change in bankfull width amongst 10 different climate models). Our original proposal envisioned developing a decision tree to reflect the culvert decision process, in order to indicate the most appropriate opportunities along that pathway to integrate climate data. However, as we learned more about the culvert design process as practiced at WDFW it became clear that focusing on the primary parameter of bankfull width would be the most practical opportunity to integrate climate projections into our design process. Projected increases in the 100-year flood should also be considered as a potentially important design parameter based on the ratio of percent change in BFW and percent change in 100-year flood.

We also had an unexpected opportunity in the course of this project to apply our data to several culvert replacement projects in the Chehalis River watershed (see Section 6 of this report and Appendix A for more detail on these case studies). We introduced our project methodology and products to the restoration managers for these culvert projects, and they agreed to size the culverts according to the new "climate adapted" estimates of future bankfull width. This process was an excellent opportunity to explore options for presenting the projections for use by restoration practitioners and engineers. We are now in the process of seeking additional resources to make our results more easily accessible to a variety of users through a web-based interface.

Background and Need

WDFW originally proposed this project because of the agency's central role in regulating the construction of water crossing structures (which are expected to last between 50 and 100 years) and the sensitivity of these structures to the changes in channel morphology anticipated from climate change. The Department issues approximately 400 permits per year related to water crossings throughout the state. In addition, the Department designs or co-designs water crossing structures throughout the state and provides technical guidance that explains how to comply with current regulations regarding fish passage.

Road crossings at rivers or streams are widely known to create barriers to fish movement when they are improperly designed or constructed. The consequences to fish populations associated with barriers at road crossings include the loss of habitat for various life history stages, genetic isolation, lack of access to refuge habitats during disturbance events or warm water episodes and local extirpation.

The importance of restoring fish passage at water crossings in Washington has been highlighted recently by *United States v. Washington* (2013), which is also known as the "Culvert Case." In the Culvert Case, Washington State government was ordered by a federal court to replace all state-owned culverts located on the Olympic Peninsula, in the Puget Sound Basin, or in the Chehalis River Basin that block 200 meters or more of salmon habitat (*United States v. Washington* 2013). About 1000 culverts are estimated to fit that description, and their replacement with culverts that pass fish is estimated to cost about $2.45 billion.

Recent studies describe the magnitude of the challenge presented by culverts both in terms of the sheer number of structures across the landscape and in the proportion of those culverts that may be barriers to fish passage. In 2015, WDFW estimated that there may be as many as 35,000 culverts blocking or impeding fish passage statewide (D. Price, WDFW, personal communication). The goal of WDFW, WSDOT, other state agencies, and tribes is to restore access to existing freshwater habitat by replacing all impassable culverts. Hence, over the coming decades thousands of culverts must be replaced. Since culverts are designed to last 50 to 100 years, depending on the type of construction, they must therefore be designed with consideration of future conditions and flows. Not doing so increases the risk of failure over time – either failure to pass fish, a catastrophic failure, and/or increases in maintenance costs over time. Please refer to Appendix A, the full final report for this project, for more background regarding fish passage and culverts in Washington.

5. Methods, Organization and Approach

Tasks 1 – 3: Project team meetings and information gathering.

Project Management – At the start of the project we held a kickoff meeting with all project team members to establish and agree on roles, responsibilities and timelines for project deliverables. One of the outcomes of this meeting was to set up monthly calls to review progress, methodology, challenges and brainstorm course corrections, as needed. These calls were helpful as the project was in its early stages to coordinate the approach among team members, and to share findings as they developed. As the project progressed, we found them less useful and met more on an as needed basis. We also determined at this kickoff meeting that a literature search of other relevant projects in the region or studies relevant to our work would be useful as we began our work. Ingrid Tohver (Climate Impacts Group) took on this task and produced the list of projects and summaries (Appendix B).

We also met with WSDOT, as a key partner in culvert design and installation, to review our plan and approach and gather ideas on how the results might be applied to WSDOT projects. This meeting was marginally useful – at this stage the project was probably too conceptual for the kind of discussions we had hoped for. We did however have a very productive brown bag talk at WSDOT once we had our project findings and products in hand. Over 20 staff participated, and we received helpful questions, suggestions and feedback. More about outreach related to this project can be found in Section 10 of this report.

Finally, as part of our preliminary information gathering, we also spoke with Regina Rochefort from the National Park Service about a project conducted in the North Cascades National Park to assess climate change impacts on road networks in the park. The meeting resulted in good background information and helped us to refine our approach.

Tasks 4 –5: Mapping decision process and determining climate screening questions

Jennie Hoffman (Adaptation Insight) of our team led tasks 4 and 5, working closely with Kevin Lautz and Don Ponder of our WDFW engineering staff. The goal was to diagram the decision process for designing and permitting water crossing structures, at a level of detail sufficient to develop climate change screening questions at appropriate decision points. The conversations and discovery process leading to the draft diagrams were useful and instructive to all team members – we learned more about potential considerations in the culvert design process, and explored which of these considerations might be climate sensitive (for example, channel width, slope, floodplain utilization, other land use and channel stability). Using the WDFW publication "Water Crossing Design Guidelines", Jennie created a draft decision tree and developed potential climate screening questions at key junctures in the design process (Appendix C). For example, when evaluating geomorphic elements in stream crossing site considerations, screening questions could include how climate change affects interactions among design elements, or how climate change might increase specific considerations, such as the "debris prone" element.

However, as our conversations continued we realized that many of the potential design considerations outlined in the WDFW guidelines represented a "best case" scenario and weren't necessarily followed in practice. In other words, these design considerations are intended to serve more as general guidance rather than as a prescriptive, step by step approach. It also became clear that WDFW engineers as well as others in the field rely primarily on the bankfull width calculation in determining culvert size. Measuring the channel width is a means of incorporating elements of the watershed such as the area, mean annual rainfall, vegetation, and the parent geology. Bankfull width is also associated with bankfull flow, which is the discharge that transports the majority of suspended and bedload sediment in many rivers. Bankfull flow recurs every 1-2 years and is the flow which has been shown to control channel form. For more on WDFW's culvert design process and a thorough discussion of bankfull flow and width, please see our final report, Appendix A, Section 2.

For these reasons, the team determined that continued development of the decision tree and climate screening questions would not be productive. Our intention was to develop a product that could be directly applied to culvert design in a time frame on which culvert work is typically conducted. We opted to narrow our focus to developing a credible and replicable process for determining projected future changes in bankfull width and presenting this information in formats that would be useful to mangers, engineers and others.

Lesson Learned

Our biggest lesson learned occurred in tasks 4 and 5. We had assigned the task of articulating our *internal* culvert design process to a team member from *outside* the agency. This put an unnecessary burden on this team member, who had to act as a sort of middle man between the engineers and our WDFW project team, and who was also put in a position of interpreting written guidelines without the benefit of understanding how they are used in practice. While we ultimately considered this part of our process a success, in that it helped us to clarify and refine how best to integrate climate into our design process, in hindsight we would rethink this task to take better advantage of our internal resources.

Task 6: Translate hydrologic projections to data critical for designing fish passage structures

WDFW teamed with the Climate Impacts Group (CIG) at the University of Washington to translate downscaled hydrologic projections for watersheds across the state into stream channel bankfull width, which is the primary parameter used by WDFW engineers and others to size culverts. Our analysis was comprised of four major steps. The first two steps, conducted by CIG, produced: 1) downscaled projections of future temperature and precipitation from 10 global climate models (GCMs), and 2) mean daily flows for

5270 uniformly distributed grid cells in Washington State using a hydrological model that relies on spatially-explicit climate projections as inputs.

The next two steps, which WDFW conducted, estimated for each grid cell: 3) bankfull flows from the mean daily flows and 4), bankfull widths from the bankfull flows. Although 100-year flood flows (Q_{100}) are thought to be accommodated by culvert designs based on BFW, we also report on the percent change in 100-year flood volumes because percent changes in BFW and Q_{100} did not vary in a consistent way. We used CIG's mean daily flow projections from the 10 GCMs to generate projections for 100-year flood volumes, and then calculated percent change between the historical estimate and the mean of the 10 projected future 100-year flood volumes for the 2040s and 2080s time periods.

For a full discussion of the methodology involved in Task 6, please see our final report, Appendix A.

6. Project Results

Projected Changes in Bankfull Width

In the two future time periods assessed, (2040s and 2080s), about 80% of grid cells are projected to have an increase in bankfull width. The mean projected percent change in BFW across the state is 4.2% for the 2040s and 6.8% for the 2080s. The changes in BFW by grid cell varied by elevation, with the largest changes occurring in high elevation grid cells with mixed rain and snow dominant hydrographs. The largest increase in percent change in bankfull width occurred in the North Cascades Ecoregion (26.7% for the 2040s and 42.9% for the 2080s) and the largest decrease in percent change in bankfull width occurred in the Columbia Basin (-15.0% for the 2040s and -20.9% for the 2080s). Please refer to Appendix A for detailed maps.

100-Flood Analysis

In the 2040s and 2080s time periods, the mean projected percent change in the 100-year flood volume (Q_{100}) is 8.0% and 16.5%, respectively. In the 2080s, the range of percent change across all grid cells is from 56 to 180%, with the biggest increases in Q_{100} projected to occur at higher elevations. The mean projected percent change for the 2040s and 2080s time periods shows distinct regional variation. For the 2080s, 2% of grid cells, mostly in the North Cascades Ecoregion, are projected to have a Q_{100} over twice as large as their historical Q_{100}. In contrast, most of the Columbia Basin is projected to have reduced Q_{100}. According to our projections for the 2080s, 35% of grid cells (over one-third of Washington) will have at least a 25% increase in Q_{100}.

Tasks 7 –9: Assessing the adequacy of current culvert design standards in light of findings and developing options to improve adequacy.

The new spatially explicit data set of projected changes in bankfull width generated as part of Task 6 allows us to evaluate some risks associated with undersizing culverts if we rely solely on current channel size. Since culverts are expected to last 50 to 100 years, if they do not accommodate future increases in bankfull width, they are at risk of being undersized and creating fish passage barriers, damage to fish habitats, require increased maintenance and repairs, or undergo catastrophic structural failure during floods. A fiscally responsible approach to incorporating climate change projections into culvert design must weigh the trade-off between the certain costs of a wider culvert now that accommodates projected changes in bankfull width versus the uncertain future costs of damages to natural resources and public infrastructure that could occur if projected future changes are not adequately accommodated.

Because the decision to build or not to build wider culverts leads to an uncertain outcome with potentially adverse consequences, that decision involves risk. Decision makers should address this risk, and our analysis provided the basis for a simple risk assessment that informs decisions regarding culvert design. We introduce the three main sources of uncertainty in our assessment as 1) the global climate models, 2) the hydrologic model and bankfull flow projections, and 3) the translation of bankfull flow to bankfull width using hydraulic geometry relationships. Our final project report (Appendix A) describes more fully why, for our purposes, we believe that the second and third sources of uncertainty are small enough to be ignored.

The greatest uncertainty lies in the climate change projections. Our project used an ensemble of 10 Global Climate Models (GCM) in order to ensure that a range of modeling approaches and climate sensitivities were included. This ensemble was drawn from the larger pool of available GCMs based on an assessment of each model's ability to capture key characteristics of the Pacific Northwest Region's historical climate. The range of projections (i.e., maximum minus minimum) for percent change in bankfull width produced by the 10 models is perhaps the simplest expression of uncertainty. Based on the range of projections, the greatest uncertainty in future changes in bankfull width occur in the higher elevations of the Olympic Mountains, the northern portion of the Cascade Mountains, and the Blue Mountains in southeast Washington, and, as expected, the range of projections farther in the future becomes wider, i.e., more uncertain.

Another simple measure of uncertainty is the number of models that agree on the sign of change. All models or no models projecting a positive change (an increase in bankfull width), corresponds to the lowest uncertainty. Half the models projecting a positive change and half projecting a negative change in bankfull width indicates highest uncertainty. In Washington, the highest model agreement occurs in mountainous regions – the Olympics, Cascades, Blues, and the Selkirks in northeastern Washington – where all models project a positive change in some grid cells, and along the margins of the Columbia Basin Ecoregion where all the models project a negative change in some grid cells.

Risk and Actionable Risk

When making decisions, managers should consider all risks, but actually eliminating or minimizing all risks may be impractical. Therefore, managers must decide which risks are "actionable." An actionable risk has three characteristics: 1) it is described by information that is specific, unbiased, credible and usable (IGES 2012); 2) the risk exceeds the manager's risk tolerance, and consequently, it gives cause or a reason for action; and 3) the risk can be acted upon, i.e., actions can be taken to eliminate or minimize the risk. We believe we have produced information that is actionable, i.e., based on the best available science that is specific to culvert design, unbiased, and credible.

Risk can be defined by two components: probability and cost. While we lack certain estimates for both, we do have projections of future conditions that can be used as surrogates. If a culvert built using today's bankfull width is too narrow to accommodate future bankfull flow and future bankfull width, then we expect that culvert's future functioning to degrade. That is, as the disparity between channel width and culvert width increases we expect the culvert's capacity to pass fish to decrease. In effect, the channel-culvert width disparity and fish passability are correlated. Eventually, the culvert's functioning may become so degraded that it no longer passes fish and damages nearby fish habitats. The ratio of future to historical bankfull widths (i.e., the percent change in bankfull width) is an estimate of the future channel-culvert width disparity at a particular location for a given time period, and hence, this ratio may be used as a surrogate for future potential cost, i.e., harm to fish populations, of not installing a wider culvert.

Because a multi-model ensemble is neither a random nor a systematic sample of GCMs, we cannot construct a probability distribution from our projections of future percent change in bankfull width. The number of models that agree on the sign of change is a simple measure of uncertainty that does not imply a probability distribution. This approach was used by the IPCC (2007), and hence, it is the approach we've employed. Our surrogate for probability is the proportion of models that project an increase in future bankfull width.

Case Study: Climate-adapted Culverts for the Chehalis River Basin

The Chehalis River Basin is currently a major focus for salmon habitat restoration, and an important part of habitat restoration in the Chehalis is replacing culverts that are barriers to fish passage. We have been fortunate to work with restoration project proponents in the Chehalis who want to design and install culverts that are adapted to future climate change. These projects have provided an opportunity for developing a procedure that translates our results into information that can be used by engineers. Please see Appendix A for a description of the procedure with a real culvert replacement project − the culvert at the intersection of Polson Camp Road and Big Creek, which is a tributary to the Humptulips River. This case study describes only the climate change information that would be incorporated into culvert design. It does not cover many other factors that an engineer should consider when designing a stream crossing, such as land uses upstream of the stream crossing, natural regrading of the stream channel, potential large woody debris transport, etc.

7. Findings and Conclusions

This report, and the projections of future percent change in bankfull width contained herein, are important potential additions to the water crossing design guidelines provided by WDFW. All models and modeling techniques described in this report were the best available. To address the potential adverse effects of climate change on fish passage through culverts, we worked with the University of Washington's Climate Impacts Group to produce essential information for the design of climate-adapted culverts. We used regionally downscaled global climate models in combination with a hydrological model to project changes in hydrology that affect changes in bankfull width. Bankfull width is the most important design parameter for water crossing structures. To avoid future damages to fish movement, fish habitat, and public infrastructure we believe that incorporating projected future changes in bankfull width into culvert design should be standard practice.

Incorporating climate change information into culvert design, or any management decision, faces obstacles. Our capacity to adequately respond to climate change is affected by temporal horizon, uncertainty, and cost. *Temporal horizon* refers to the future point in time beyond which events, however likely, do not compel policy makers or managers to take action. In other words, they cannot think beyond the temporal horizon. Major climate change impacts are projected to occur decades from now, which is beyond the temporal horizon of most policy makers. Our bankfull width projections, for instance, are for the 2040s and 2080s time periods − roughly 30 and 70 years from now, respectively. Even though the service life of many culverts is expected to be 50 to 100 years, our projections may be beyond the temporal horizon of some policy makers, managers, or engineers.

As explained earlier, uncertainty forces a consideration of trade-offs between the certain costs of adapting to future climate change now versus the uncertain costs incurred by not adapting to future climate change. If we were absolutely certain about when, where, and how much bankfull width would increase, then the decision to install wider culverts would be much easier. How uncertainty should be dealt with is very subjective. At many stream crossings the mean projected percent change in bankfull width may be below the actionable risk threshold of some managers (e.g., less than 5 or 10 percent change), however, a risk-averse approach that considers worst-case projections might compel action and prescribe a wider culvert at those same stream crossings.

Cost is perhaps the greatest obstacle to climate adaptation. If climate adaptation could be accomplished with no additional costs (monetary or nonmonetary), then there would be no reason not to do it. Our recent experience with helping culvert project proponents in the Chehalis River Basin may be atypical. WDFW worked with several project proponents in the Chehalis Basin. We provided them with the mean projected percent change in bankfull width for 30 culvert locations and explained how to use that information. All project proponents were eager to obtain those projections and seemed committed to using that information in culvert design. However, it should be noted, that for these particular projects the additional costs of wider culverts will be covered through an increase in state government funding. To garner the same level of eagerness and commitment to climate-adapted culverts throughout Washington, additional state or federal funding may be needed. Washington's Salmon Recovery Funding Board (SRF Board) has taken a step in that direction by requiring project proponents to explain how their habitat restoration projects (including culvert replacement) will be adapted to future climate change. This implies that the SRF Board may be willing to cover the additional costs of climate adaptation.

We explored the relationship between increased culvert width and increased culvert cost. Our estimate is based on a very simple situation: a stream simulation culvert constructed with a round (circular cross-section), steel, corrugated pipe on a single-lane gravel road. We found that the ratio of increase in culvert cost to increase in culvert width is 1.2:1. Hence, for each 10% increase in culvert width, culvert cost increases by 12%. The slope of this relationship may increase for more complex situations (e.g., multilane highway, concrete box culvert). The cost to replace 1000 state-owned culverts covered by the Culvert Case was estimated to be about $2.45 billion. In the area covered by the Culvert Case, the mean of mean projected percent changes in bankfull width is about 10% for the 2080s time period. If we assume that nearly all new culverts will be stream simulation culverts, then the additional cost for climate-adapted culverts covered by the Culvert Case could exceed $200 million. While the immediate additional cost of climate-adapted culverts may be disconcerting, that cost may be much smaller than the future cost of replacing culverts (again) that become fish passage barriers because they cannot accommodate increasing streams flows and changing channel morphology.

Culverts are a major concern in Washington because they lie at the intersection of three major natural resource management issues: the management of anadromous salmon species, some of which are federally-listed threatened species and all of which are commercially valuable fisheries; maintaining Indian treaty rights to have "fishery habitat protected from man-made despoliation" (*United States v. Washington* 1980); and climate adaptation of public infrastructure. In response to salmon species' listings under the federal Endangered Species Act, state and local governments, major landowners, and nongovernmental organizations throughout Washington have increased their efforts to replace the estimated 35,000 culverts that form fish passage barriers. Many of these culvert barriers were the result of old designs which we now know were entirely inadequate. The current urgency regarding culvert replacement is also influenced by the Culvert Case (*United States v. Washington* 2013) which forced state government to expedite the replacement of culvert barriers. Replacing barriers with fish-passable culverts provides access to hundreds of miles of unoccupied habitat for threatened salmon species and should enhance both commercial and sport fisheries. If culverts replaced today are not designed to accommodate future changes to stream flow and channel morphology caused by climate change, then new culverts may become barriers sometime in the future. This would be a costly repeat of past mistakes.

8. Recommendations for Future Work

Dissemination of Project Results

To more efficiently disseminate this project's products we would like to develop an internet site. The simplest option is an internet site that allows users to download data files containing the projected percent changes in bankfull width for the entire state. A much more sophisticated option is a site that allows users to point and click on a culvert's exact location and the site's software then performs all the calculations for determining projected percent change in bankfull width at that location (watershed delineation, area intersections, area-weighted average, etc.). Whatever internet-based service we develop, we will continue to work with proponents of culvert projects to help them design climate-adapted culverts.

To encourage greater use of this project's products, we hope to add a chapter on climate adaptation to WDFW'S current water crossing design guidelines. That chapter would explain the information we have developed and explain how to incorporate it into culvert or bridge design. It would also cover how to use the results of the 100-year flood analysis in water crossing design.

Updating Climate Science

Climate change science is one of the hottest topics in science, and consequently, it is constantly advancing. New climate change projections are produced periodically, and we hope that the Climate Impact Group updates their state-wide hydrological projections as new climate change projections become available. A major issue in climate change modelling is the best way to express uncertainty. We followed recommendations for expressing uncertainty, but current methods are not entirely satisfactory. As methods for expressing uncertainty advance, we hope to incorporate those advances. We could also explore enhancements to the hydrological modelling. Land cover is a major variable in VIC, but we currently use 1992-1993 land cover data which are also static in time. We could simulate changes in land use, such as increased urbanization, and the resulting hydrological response over time.

Understanding the Consequences of Undersized Culverts

With respect to culverts and climate change, WDFW's principal concern is the loss of fish passage and damage to fish habitat caused by undersized culverts. At present, we use the ratio of future to current bankfull width as a surrogate for future potential cost, i.e., harm to fish populations, of not installing a wider culvert. We must use a surrogate for damage or harm because we lack empirically-derived relationships that describe how fish passage changes as a function of the culvert-channel width disparity. If fact, there are no empirical studies describing stream channel behavior in no-slope culverts and only one inconclusive study on stream channel behavior in stream simulation culverts.

Hence, we do not fully understand how increases in the channel-culvert width disparity affect movement, scour, or aggradation of sediment and consequent fish passability. Lacking this knowledge, we cannot estimate the actual risk of undersized culverts due to climate change. There are two approaches for closing this knowledge gap. The first is modelling stream flow and sediment transport in culverts (e.g., Rowley et al. 2014). We have explored the acquisition and use of two-dimensional simulation models of sediment transport but currently lack funding to pursue such work. The second approach is empirical study. We are currently in the fourth year of long-term effective monitoring of recently installed no-slope and stream simulation culverts. Some questions about the relationships between culvert width and sediment transport can be answered through long-term monitoring.

Improving Information on risk and cost

The information we have developed for designing climate adapted culverts should be considered the best-available science on this issue. However, we do not provide key information that many decision makers would like to have when considering the risk, cost, and trade-offs associated with climate-adapted culvert design. As explained above, we have only a simplistic estimate for the cost of installing wider culverts and we cannot currently project all ecological consequences of an undersized culvert. To address the former, we could develop cost estimates for a wide variety of culvert replacement situations. To address the latter, computer modelling may be the best short-term approach. We would like to tackle both tasks, but that is contingent upon funding.

9. Management Applications and Products

We expect the methodology and findings from this project to be applicable and of interest to a variety of potential users. As described above, we have already begun using these findings at WDFW. We have been working with restoration managers in the Chehalis watershed to use our results in sizing culverts to ensure that they will be adapted to future climate change. We have also been working internally with our Lands Management staff to educate them on the project methodology and findings. Managers have agreed in concept to use the projections of future BFW when replacing or installing culverts on agency owned lands, as long as increased costs can be factored in at the outset of project design. WDFW manages nearly 1,000,000 acres of lands, and we expect several culvert projects in the coming years.

We have also been reaching out to the Washington State Department of Transportation (WSDOT). WSDOT staff who are involved in fish passage culvert installations have expressed interest in following our work and in using our products. They also recommended we reach out to the Federal Highway Administration, which is on our "to do" list.

Washington's Salmon Recovery Funding Board (SRF Board) has also expressed interested in ensuring that the salmon recovery projects which they fund will be resilient to future changes in climate. The SRF Board requires project proponents to explain how their habitat restoration projects (including culvert replacement) will be adapted to future climate change. This implies that the SRF Board may be willing to cover the additional costs of climate adaptation.

Different stakeholders may view risk, cost, and trade-offs associated with climate-adapted culvert design very differently. For instance, from WDFW's perspective the foremost risk is that associated with installing an undersized culvert that becomes a barrier to fish movement sometime in the future. For the culvert owner − which can be state, county, or city governments or a private entity − the foremost risk might be the additional cost of installing a culvert that is larger than necessary. While we recognize both perspectives on risk, we have focused on informing the Department's climate adaptation strategies for maintaining or restoring fish passage at stream crossings. A meeting amongst state government agencies, local governments, tribes, and various stakeholders is needed to discuss an effective and equitable plan for installing new culverts that are wide enough to accommodate future changes in stream flows and channel morphology.

10. Publications and Outreach

Tasks 10-12: Prepare a written report, Plan two workshops, and disseminate findings more broadly

Final Written Report

Appendix A represents our full written final report. We intend to submit a version of this report for publication in a scientific journal.

Workshops

We held two formal workshops as part of this project – each at two different phases of the project. The first was held on June 3rd, 2015. This first workshop was invitational and our intent was to present our methodology and draft findings to a technical audience for review and substantive feedback. We invited researchers and practitioners familiar with issues related to culvert replacement and climate change. Approximately 25 people attended, including hydrologists, engineers, climate scientists, and restoration practitioners.

The second workshop was held in November of 2015 and our invitation list was much wider. Our product results were much more refined at this stage, and we were interested not only in feedback on how to make our results stronger, but also to disseminate these findings to individuals and organizations who might be able to apply them to their own work. Approximately 20 people attended, including representatives from WSDOT, WDNR, the Seattle Public Utilities and King County, *Project presentations made by team members:*

- 2015 NW Climate Conference, Couer d'Alene, Idaho, November 2015, approximately 60 attendees.
- 2016 River Restoration Northwest, Skamania, WA, February 2016, approximately 400 attendees.
- 2016 Multiple presentations to management teams at WDFW – Our intent was to gain buy-in on using climate adapted designs for all culvert replacements on agency owned land.
- 2016, Chehalis Basin Habitat Work Group, March 2016, approximately 20 attendees.
- 2016, American Fisheries Society regional meeting, March 2016, approximately 40 attendees.
- 2016, Washington Coast Sustainable Salmon Partnership, April 2016, approximately 20 attendees.
- 2016, Association of Climate Change Officers, Richland WA, approximately 65 attendees, June 20th.
- 2016, WSDOT, brown bag presentation for WSDOT, July 2016, approximately 20 staff attended.

Webinars

We held an NPLCC webinar on June, and over 200 people signed up. The slides and available project information were posted on the NPLCC web site.

Signature: *Lynn Helbrecht* (Hard copy to be sent in the mail).

11. Appendices

APPENDIX A: (Separate Document)

APPENDIX B: Preliminary Literature Review – projects and research relevant to the NPLCC/WDFW Project to integrate climate change into design and permitting of water crossing structures.

Prepared by Ingrid Tohver, Climate Impacts Group, October, 2014

1. Developing a GIS-based Geospatial Decision Support tool for Assessing Climate Change Impacts on Flood Risks in Northern Cascadia Road Networks

http://www.cfr.washington.edu/research.cesu/projects/project_detail.asp?agency=NPS&project_identifier=P13AC00706

This project is funded the PNW Cooperative Ecosystem Studies Unit (CESU) and is a collaborative effort between the UW and the NPS/NFS.

- The objective of this project is to develop a GIS-based tool to assist management decisions related to road infrastructure and climate-induced changes in flood risk.
- GIS-Hydroads will utilize a database of road inventory and overlay output from a regional hydrologic model, depicting flood risk spatially
- A pilot project in the Cascade basin on a western slope of the North Cascades is being implemented for analysis of feasibility
- GIS-Hydroads is designed for expansion throughout the western U.S.
- Full implementation of GIS-Hydroads will help identify and prioritize infrastructure improvement and areas of habitat restoration

2. Prioritizing restoration and enhancement of passage at stream-road crossings for aquatic vertebrates in the face of changing hydrologic regimes in the North-Pacific Landscape Conservation Cooperative

Project url:
https://nplcc.blob.core.windows.net/media/Default/2013_Documents/Prioritizing_Restoration/FY13_USGS_Fish_Passage_Project_proposal.pdf

This project is a precursor to our current project covering the design of stream crossing structures in the NPLCC region under projected climate change conditions

- Project objective is to provide new tools to managers that compare cost-benefit tradeoffs based on the anticipated impacts of climate change and the associated uncertainties
    i. Project focuses on stream crossings in the Siuslaw National Forest (SNF), but is designed to be expanded/applied across NPLCC domain
    ii. Maintaining habitat for fish passage is the primary consideration for stream crossing in SNF
- In an iterative process with FS, state, local and tribal collaborators, the project will develop a conceptual model

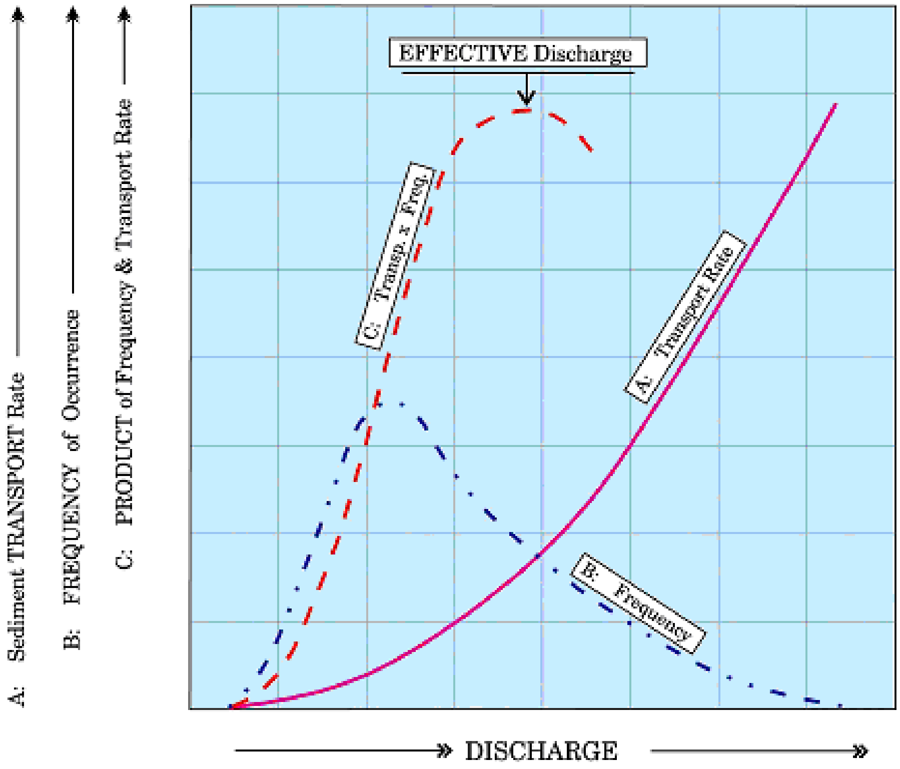
i. Model evaluates biological, structural (stream crossing design) and economic costs/benefits associated with climate change scenarios
ii. Biologic aspect investigates models of species presence and abundance around crossing to evaluate restoration actions
iii. NetMap used to determine hydrologic/geomorphic component of analysis (ie. probability of failure)
iv. Model output used to Climate change impacts, vulnerabilities and uncertainties

3. EPA: Hydrologic Processes: Bankfull Discharge

Report url: http://water.epa.gov/scitech/datait/tools/warsss/bankfull.cfm

- Informed by Dunne and Leopold (1978): "The bankfull stage corresponds to the discharge at which channel maintenance is the most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work results in the average morphologic characteristics of channels."

- Bankfull discharge is associated with a momentary maximum flow that has an average recurrence interval of 1.5 years as determined using a flood frequency analysis (Dunne and Leopold 1978). *Modest flow regimes transport greatest quantity of sediment material over time (Wolfman and Miller 1960):



Relationship among Discharge (x-axis), Sediment Transport Rate (A), Frequency of Occurrence (B) and Product of Transport Rate and Frequency of Occurrence (C). Figure shows that greatest work of sediment transport occurs at moderate flow rates.

- Study in Canada indicates Bankfull Discharges have average return interval of 1.6, ranging 1.5 – 1.7 years. (Lower return interval for urban streams – 1.1 yr).

4. Streamstats for WA State

Url: http://water.usgs.gov/osw/streamstats/ssinfo1.html

- This is an application that uses GIS to estimate basin characteristics (drainage area) and historical annual precipitation to develop a regression equation to calculate Q2 – Q100
- WA State divided into 9 climatically distinct regions, resulting in 9 unique regression equations
- Gaged sites can be used as proxies for ungaged sites, if ungaged site in within 50% of the gaged drainage area
- Uses a mapping tool to identify and calculate flood statistics for watersheds throughout the state
- References:
  - **i.** Knowles, S.M. and Sumioka, S.S., 2001, The National Flood-Frequency Program—Methods for Estimating Flood Magnitude and Frequency in Washington, 2001: U.S. Geological Survey Fact Sheet FS-016-01, 4 p.
  - ii. Sumioka, S.S., Kresch, D.L., and Kasnick, K.D., 1998, Magnitude and Frequency of Floods in Washington: U.S. Geological Survey Water-Resources Investigations Report 97-4277, 91 p.

5. Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I

Project url:
https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/

This project takes a risk assessment approach:

- Problem - Account for uncertainties in climate modeling – timing and magnitude of events. Deterministic methods for decision-making cannot accommodate a range of conditions.
- Solution – Adopt iterative risk management approach. Provides guidance on risks to infrastructure and its resilience.
- Tool: Conceptual framework for climate impacts to transportation.
  - i. *Exposure* is the **magnitude** of stress on system as a result of a climate change factor (e.g. SLR, higher temperatures, rising storm intensity). It accounts for the **probability** of system exposure.
  - ii. *Vulnerability* is the potential for damage or disruption of structure if exposed?
  - iii. *Resilience* is the current system's capacity to absorb disruption without lowering transportation performance.
  - iv. *Adaptation* is the effort to boost resiliency of facility and of system to changes anticipated from climate change.

6. Oyster River Culvert Analysis Project (2010)

Report url:
http://www.prep.unh.edu/resources/pdf/oyster_river_culvert-prep-10.pdf

Pilot project for Climate Ready Estuaries (EPA) performs climate change analysis for case study using Oyster River in NH.

- Compares two approaches to design implementation: business-as-usual vs. LID
- Uses output from 1 Coupled Climate Model (CCM) under 2 emissions scenarios (moderate A1b and fossil fuel intensive A1fi

- Run-off (RO) and peak flow (PF) estimated with NRCS TR-55 method
    - i. Precipitation data fit to probability distribution to determine intensity-duration-frequency (IDF) relationship
    - ii. IDF derived for baseline (NCDC data) and for future (downscaled CCM data for 2060s) to compare 25-year storm values
    - iii. Culverts in case study designed to 25-year storm (or 4% probability) in 24 hrs.
    - iv. Calculated % change of 25-year storm from baseline to 2060s
    - v. Peak run-off rate estimated from HEC-22 manual

7. Culvert model
    - i. Field data collected on culvert inventory: geomorphic, physical, site characteristics, etc.
    - ii. Culvert designed to convey specific maximum flow from design storm (25-yr event in 24-hours for NH)
    - iii. Culvert model estimates minimum cross-section needed to convey peak flows (sizing methods from NH Design Guidelines, 1996).
        1. Inlet control is primary design assumption
        2. Culvert sizing calculated using Federal Highway manual
    - iv. Culverts determined undersized if actual cross-sectional area of current culvert > modeled cross-sectional area
        1. Expressed as ratio: current-to-modeled (C/M)
        2. Metric of vulnerability

- iii. Threshold analysis
    - i. Decision-support tool that depicts impacts to infrastructure as a continuum and overlays adaptation strategies at specific points along continuum
    - ii. C/M can be used as part of vulnerability assessment: Risk = exposure x probability.
- iv. Uncertainty in projections not a barrier to action (cost of resizing) in this study

7. Design Hydrology for Stream Restoration and Channel Stability at Stream Crossings

Project url: http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3426

This project is funded by the Transportation Research Board

- Sediment loads (90%) predominantly carried/deposited by events occurring with < 5-year return frequency (Wolman and Miller 1960)
- Bankfull stage defined by ~2-year event or more frequent based on annual peak flow series (effective discharge)
- Land-use changes associated with urbanization, mining, agriculture and forestry operations affect the sediment deposition and flow metrics (peak annual flood, flow reductions, flow-duration curve, total runoff etc.) of streams
- Many state DOTs design hydraulic structures based on bankfull width or effective discharges, but do not consider stream geomorphologic or flow modifications associated with land-use change
- Objectives of this project involve incorporating anticipated changes into hydraulic design
    - i. Investigate alternative flow metrics that are more correlated to channel forming processes (eg. distribution of daily mean discharge, flow duration curves)
    - ii. Develop quantitative method to estimate land-use change impacts
    - iii. Determine how changes will affect bankfull width

8. An Economic Analysis of Improved Road-Stream Crossings (2013)

- This report by The Nature Conservancy presents quantitative and qualitative info on social, economic and environmental benefits of improving stream crossings designed for climate change resilience
- Observed increase in extreme P event frequency and intensity over last 50 years in Northeast
- Report by National Cooperative Highway Research Program (NCHRP) recommends redesign of culverts to accommodate both fish passage and new patterns of P (Meyer et al. 2011).
- Upgraded stream crossings can be less expensive than undersized counterparts in long-run, even more so considering CC
- Study uses Ausable watershed in Adirondacks and damage from Tropical Storm Irene (2011) as case study
    i. Compares cost of replacing culverts in kind vs. improved design
    ii. Finds that upgrading structures for CC resilience can be more cost effective in long run
- Supplies examples from other regions
    i. Minnesota: stream simulation design technique (mimics streams natural channel) adds 10% to cost of conventional design
    ii. Maine: cost of replacing culverts with 1.2x bankfull width adds 80-295% of in-kind replacement
    iii. Tongass NF, Alaska: stream simulation design costs 20-30% than hydraulic design for streams >3% slope (little difference for slopes <3%)
    iv. Oyster River, NH: cost to replace undersized culverts with regard to projected changes in P is 42-49% more costly than in-kind replacement
    v. WA State: cost of improving culverts that act as fish passage barriers to Tribal fishing streams (no comparison made to in-kind replacement)

9. Climate Change and the Highway System: Impacts and Adaptation approaches, NCHRP Meyer et al. (2011)

Report url: http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-83(05)_Task2-3SynthesisReport.pdf

- The FHWA recommended that a 100-year design frequency be used for interstate, major structures and critical bridges that would consider a combination of wave and surge effects, as well as the likelihood of pressure scour during an overtopping event (water levels going over the structure). The consideration of a super flood frequency surge and wave action (that is, the 500-year design frequency) was also suggested. It was also recommended that risk and cost assessments be conducted.
- Heavy precipitation and increased runoff during winter months are likely to increase the flood damage to tunnels, culverts, and coastal highways (CNRA, 2009).
- More intense precipitation events in areas of high impervious cover could result in runoff spikes that can cause increased erosion in streambeds and, in warm weather, thermal shock to water bodies from the sudden infusion of pavement-heated runoff. It may also result in pollutant loading spikes, particularly if rainfall events become less frequent.
- Recommended adaptation strategies:
    i. Incorporate CC into long-range planning
    ii. Improve design standards – few specifics (eg. Maine DOT recommends using Q100 rather than Q50, King County using CC in designs of bridges and culverts)
    iii. Retrofit structure – eg. WA DOT strategy focuses on restoring natural processes
- King County Road and Services Division
    ii. Replacing or rehabilitating bridges in order to improve floodwaters conveyance and to avoid scour during high flows.
    iii. Using pervious pavement and other low impact development methodologies to manage stormwater through reduced runoff and on-site flow control.

    iv. Modifying existing seawalls to avoid failures in transportation facilities.
    v. Evaluating roadways to minimize their vulnerability to potential risk from landslides, erosion, or other failures triggers.
    vi. Developing new strategies to effectively respond to increasingly intense storms, including providing alternative transportation access.
    vii. Managing construction and operations to minimize effects of seasonal weather extremes.
    viii. Identifying opportunities to incorporate habitat improvements that buffer the effects of climate change on ecosystem health into project designs.
  i.

10. Adapting to CC: Strategies from King County, WA (2009)

Report url: http://www.nerrs.noaa.gov/doc/pdf/training/strategies_king_county.pdf

- King County is taking action now to make its transportation system more resilient to the effects of climate change. The new $24 million Tolt Bridge spanning the Snoqualmie River has been built with longer spans than the previous bridge, increasing its capacity to withstand high flows and major flooding events. More than 57 smaller "short span" bridges are planned to be replaced with wider span structures, allowing debris and floodwater to pass underneath without backing up river levels.
- In addition, the county is tackling culverts that will increasingly be at risk for chronic flooding, road failure, and destruction of fish habitat during storm events. The county's Department of Transportation Road Services Division (RSD) is replacing these culverts with larger systems not only to prevent roads from failing, but also to improve fish passage.

11. Climate Change Vulnerability and Adaptation in the North Cascades Region, WA

Report url: http://www.fs.fed.us/pnw/pubs/pnw_gtr892.pdf?

- A report by the PNW Research Station identifying the projected impacts of CC in the NCAP region; and finding strategies to increase the resilience of ecosystems to those impacts
- Identifies projections of increasing flood magnitude and frequency as major threats to current infrastructure (roads and culverts) in NCAP region
- Engineers in MBSNF and OWNF are replacing failing culverts and bridges and decommissioning roads to mitigate impacts on aquatic systems
    i. Current efforts focused on inventory of infrastructure (roads, culverts, etc.) for identifying/prioritizing future repairs, replacements and upgrades
    ii. Engineers may consider prioritizing upgrades in mixed rain-and-snow basins (Littell et al. 2012)
    iii. Consider also culvert designs that incorporate estimates of Q100 derived from future conditions projected by hydrologic/climate model output
        1. Non fish-bearing streams are sized for historical Q100 + factor related to expected debris loads
        2. Another tool: maps of spatial variability of flood risk to identify priority areas to increase culvert size
    iv. Fish-bearing streams in NF subjected to ESA standards
        1. Culvert design based on stream simulation design standards, resulting in openings that far exceed Q100
        2. Exemplifies “no regrets” strategy
    v. Barriers to implementation
        1. Emergency Relief for Federally Owned Roads (EFRO) funding for “betterments”, or replacement of damaged structure with more resilience to higher flows
        2. ERFO only replaces “in-kind” structure

    3. Climate science should be considered when justifying betterments

12. Olympic Peninsula Fine-Scale Hydrologic Extremes Project

- This project was a joint effort by the Olympic NF/NP and CIG to develop fine scale hydrologic extreme projections for culvert management/design in the region
- Datasets include extreme projections for the Olympic Peninsula
    i. Includes historical (1970 – 1999) and three future time periods (2020s, 2040s, 2080s)
    ii. Two resolutions: 1/16 degree grid cell (~11.5 sq. mi), 12-digit HUC
    iii. Flood statistics (Q100) and low flows (7Q10) calculated
- The results were validated using USGS and HCDN data for 6 case basins
- Developed a hybrid product using VIC hydrologic estimates of % change in flood magnitudes applied to Streamstats results
    i. Streamstats is a regression-based tool to calculate Q100 using historical precipitation and basin characteristics data (does not capture projected changes in climate)
    ii. Hybrid product useful because applies climate change data to familiar tool used by NF/NS managers

13. WA DOT: Adapting to a Changing Climate

url: http://www.wsdot.wa.gov/SustainableTransportation/adapting.htm

- WA DOT received funding from FHWA to identify infrastructure vulnerable to projected climate changes
- Used scenario planning (from CC projections) to qualitatively assess risk to transportation infrastructure in multiple workshops
    i. Conducted inventory survey of state's transportation infrastructure
    ii. Used cost estimate and risk assessment to determine at risk infrastructure
    iii. Applies conceptual model on qualitative risk and vulnerability by adapting FHWA methodology (Figure below, based on FHWA item listed in number 14)
    iv. Assessment of each inventoried asset and risk posed by CC is spatially depicted (draft map on website)

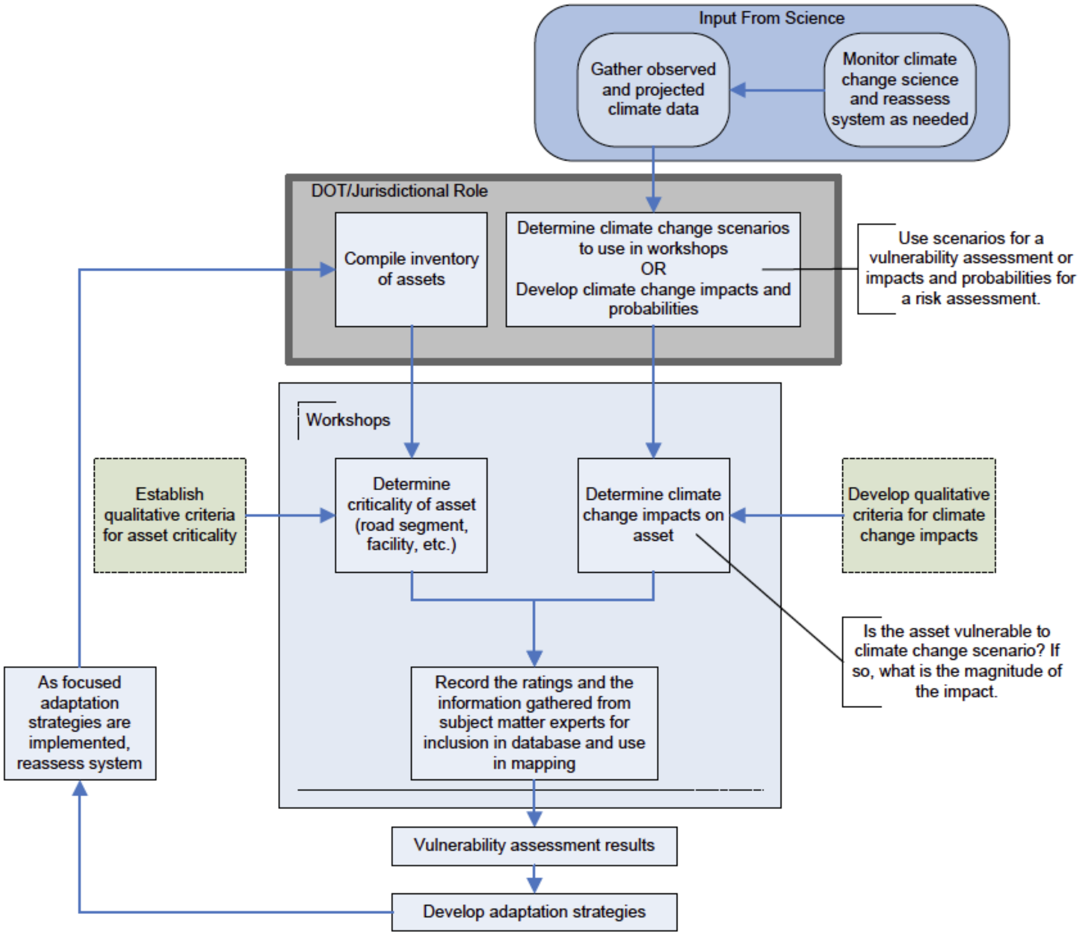


Exhibit 3-2 WSDOT Recommended Vulnerability Assessment Methodology

14. Other projects of interest

Maine Stream Habitat Viewer*: http://mapserver.maine.gov/streamviewer/streamdocHome.html*

UMass Extension's River and Stream Continuity Project: *http://www.streamcontinuity.org/index.htm*

FHWA Assessing vulnerability and risk of CC effects on transportation infrastructure:
http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/vulnerability_assessment_pilots/conceptual_model62410.cfm#fig1

APPENDIX C: Preliminary climate risk screening of the WDFW water crossing siting and design process

prepared by Jennie Hoffman (Adaptation Insight), June, 2015

Introduction

The Water Crossing Design Guidelines were developed to reduce the risk that water crossing structures become barriers to aquatic organism passage. Culverts become barriers for a variety of reasons, including aggradation, scour, formation of perched inlets or outlets, or blockage by large wood debris. The assumption is that under existing conditions, current design guidelines should lead to culverts that have a minimal risk of become fish passage barriers over their design life. The question is, what if conditions change? Do culverts designed for current conditions have an increased risk of failure under climate change, and is the increased risk enough to worry about?

To explore this question, we performed a climate risk screening of the siting, crossing type, and culvert design decision process as practiced in Washington State. Climate risk screening of the water crossing siting and design process was conducted using the following process:

1. Map the current culvert siting and design process based on WDFW's 2013 Water Crossing Design Guidelines and interviews with staff.
2. Identify inputs to the decision process that are potentially sensitive to climate change ("asking the climate question"), i.e. where the decision would potentially change were climate change considered.
3. Determine at a coarse scale which of those sensitivities pose sufficient risk to fish passage performance (the focus of this project) to merit further investigation.

For the purposes of this phase of the risk screening we will assume that the process outlined in the Guidelines is implemented perfectly every time, and assess where climatic changes or effects might affect culvert performance. In reality, the process varies depending on whether WDFW is responsible for culvert design or is issuing a permit to another entity. We will explore sources of risk related to factors other than culvert design later in the document.

The process

The basic decision process leading to a final culvert design (Figure XXX illustrates the first three steps) has four basic steps:

1. Determine whether the crossing is necessary
2. Determine an appropriate crossing location
3. Determine the most appropriate crossing type
4. Design the crossing to meet fish passage requirements

For each of these steps we can look at what information and criteria are used for the decision, and how climate change might influence those input variables.

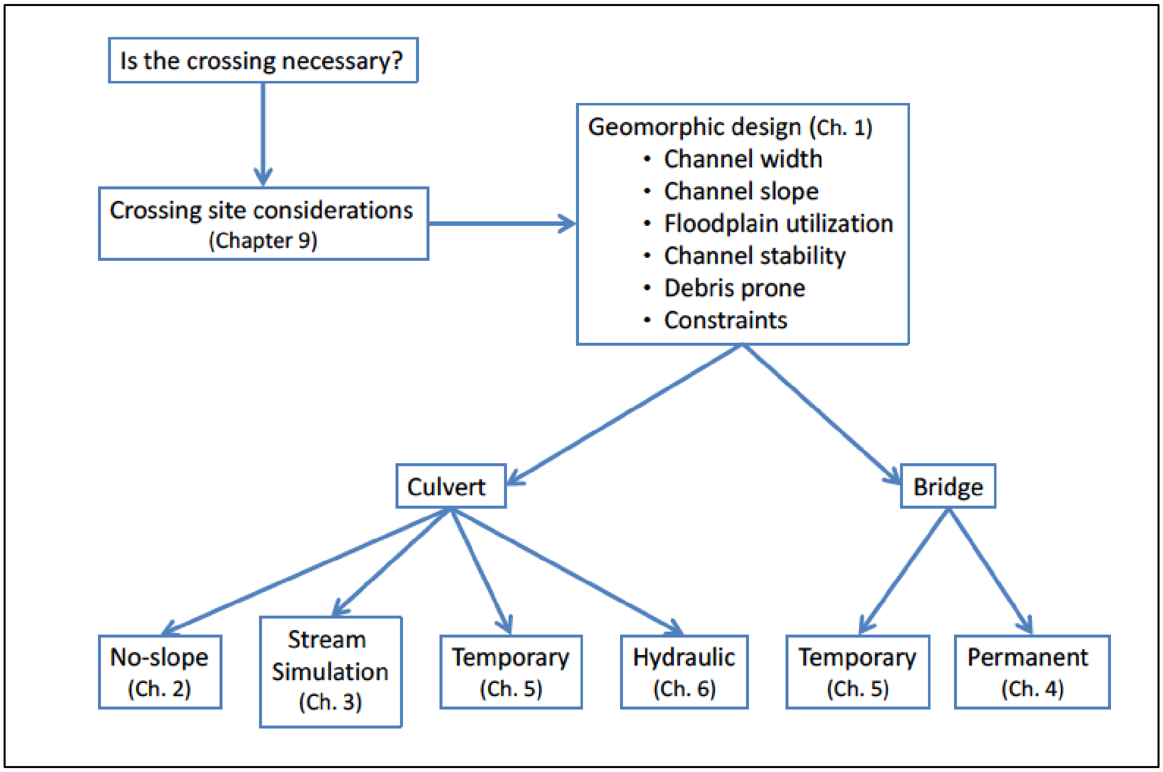


Figure 1. Flow chart for selecting a crossing method. Taken from 2013 Water Crossing Guidelines

Potential climate sensitivities

Table AAA shows the inputs to each crossing decision and examples of "climate questions" that could be asked at each stage. Decisions about crossing necessity and location are based primarily on best professional judgment, while decisions about crossing type involve both best professional judgment and quantitative guidelines. Final culvert design is primarily based on quantitative inputs.

The point of "asking the climate question" is to identify and assess potential risks so that there are as few unmanaged major risks as possible. In the case of culverts, most of the input variables are potentially climate-sensitive, although our ability to model or project responses for many of them is not yet well-developed. Thus assessing risk will depend on both climate modeling and expert elicitation of probabilities.

Based on interviews of WDFW staff, BFW seemed to be the most important consideration for fish passage performance. It integrates a variety of watershed characteristics and processes, and culverts sized based on BFW are likely to accommodate natural flow and channel processes within the culvert. Also important is debris proneness, as this influences the likelihood of the culvert becoming blocked. Culverts are required to be tall enough to pass the 100-year flood with consideration of debris; typically "consideration of debris" is incorporated into height calculations by adding an extra one, two, or three feet above the 100-year water surface depending on culvert width.

Table BBB goes into more detail on how climate change might affect each of the geomorphic design elements. The first two, BFW and 100-year water surface, are primarily a function of runoff, which is in turn a function of precipitation, land cover, soil type, and snow- and ice-melt (Figure YYY). The most direct link between climate change and changes in runoff is through precipitation. Climate change is expected to influence the timing, type, and intensity of precipitation. Climate change also changes the snowpack volume and timing of snow- and ice-melt. Changes in both of these factors are commonly incorporated into runoff models.

Climate change is also likely to influence runoff less directly through changes in land cover and soil condition. Some of these changes would occur slowly and over longer time periods, such as changes in vegetation type and cover as a result of changes in temperature and precipitation. Other changes will likely occur sooner and more rapidly, such as the vegetation of areas previously covered by snowfields and glaciers, or the shift of shrubs and trees into alpine meadows. Perhaps the most immediate and influential effect will come from the increased frequency and intensity of wildfires. Runoff, sediment input, and volume of large woody debris all increase for a period of several years following large fires.

Interactions between climate-related changes and other land use changes, such as increased urbanization and increases or decreases in logging or grazing, could also be important, although the nature of those interactions has not been explored in depth.

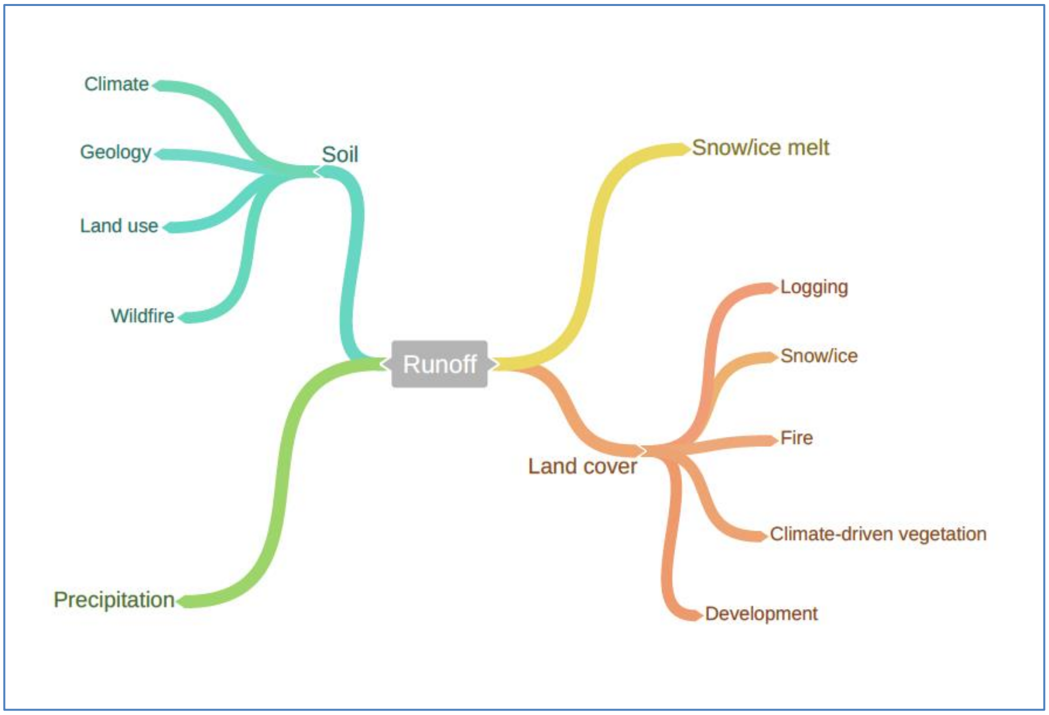


Figure 2. Factors influencing runoff

Identifying key climate risks

Understanding the actual risk related to the potential sensitivities identified above is difficult because we have an incomplete understanding of how exactly culvert failure happens. In particular, because the use of stream simulation and no-slope culvert design in Washington State is relatively recent (compared to culvert design life), we have limited information on how well those culverts maintain bed continuity with the surrounding channel over time. To more effectively identify the most important sources of risk and the actual likelihood of failure, we need more information on how stream simulation and no-slope culverts fail, and under what conditions. This would allow the identification of performance metrics that could be used in a more formal risk assessment.

That said, assuming that the biggest sources of climate risk relative to aquatic organism passage is from changes in BFW, 100-year water elevation, and debris proneness, performance metrics by which to assess failure risk include whether culvert width remains larger than BFW under future scenarios, and whether culvert height remains greater than the 100-year water elevation under future scenarios.

In the next section of this report we address the first of those performance metrics by projecting future BFW under multiple climate projections. The models used for these projections do not capture changes in land cover, so the projections do not capture risks associated with increasing wildfire intensity and frequency, changing vegetation, or land use changes. Nonetheless, these projections provide a starting point from which to explore potential risks and adaptation options.

Table 1. Culvert decisions, inputs, and climate considerations

Decision	***Input***	***Climate considerations***
Crossing necessity	• Existing crossings • Legal/regulatory constraints • Needs of people and businesses	• Might climate change affect land use in ways that influence the necessity of the crossing? This might happen e.g., if timber harvest plans changed in response to increased wildfire frequency or decreased slope stability in response to increasing precipitation
Crossing location	• Channel stability • Cumulative impacts • Critical area locations • Need to constrain, re-align, or alter natural channel	All input variables are potentially sensitive to climate change. Possible "climate questions": • Might the location, size, or importance of critical areas change as a result of climatic changes? • Might new areas be considered critical in light of climate change? No longer be considered critical? • How might climatic changes and effects influence channel stability?
Crossing type • Bridge • No-slope culvert • Stream sim culvert • Hydraulic culvert	• Channel width (BFW) • Channel slope • Floodplain utilization ratio (FUR) • Channel stability • Debris proneness • Constraints	Other than constraints, all input variables are potentially sensitive to climate change. Possible "climate questions": • The Guidance provides suggested values (qualitative for width, slope, and FUR, quantitative for other variables) that determine which type of crossing is most appropriate. Might climatic changes or effects "flip" the appropriate type from one category to another? • Channel slope/longitudinal profile is used to create the expected regrade line. Would the expected regrade line change as a result of climatic changes or effects? • Might climatic changes or effects change the interactions among geomorphic variables in ways that would affect the choice of crossing type?
Culvert design • Width • Height • Box/arch/pipe • Metal/concrete • Bed design	• BFW • Debris proneness – or – 100-year water surface	• The design standard for debris loading is the 100 year peak flow debris loading. How might land use and climate change alter both the 100 year peak flow and the debris loading associated with that flow?

NB: we did not address decisions related to culvert bed design or culvert material in this study.

Table 2. Geomorphic design elements used in the culvert decision process, and potential implications of climate change

Geormorphic factor	***Design element affected***	***Possible climate change effects***
Bankfull width (BFW)	• Crossing design type (bridge, stream sim, no-slope, hydraulic) • Width	• Reflects runoff, which will change as a result of direct and indirect effects of climate change.. Roughly the Q1.5 in fluvial channels. • Will the relationship between current measured BFW and failure risk change?
100-year water surface	• Culvert height; used by those who don't or can't calculate actual debris proneness.	• Reflects runoff, which will change as a result of direct and indirect effects of climate change.
Debris proneness ○	• Crossing design type • Width • Height	• How might changes in land use and climate affect both the 100-year peak flow and the debris loading associated with that flow? • How might increased fire in the watershed affect LWD input? • What about the combo of fire and increased precip? • What about loss of snowpack, glaciers?
Channel slope	• Crossing design type	
Floodplain Utilization Ratio (FUR)	• Crossing design type	• Reflects floodplain width, which is unlikely to change as a result of climate change, and BFW, which is.
Channel stability • Both vertical and horizontal	• Crossing design type	• Changes in flow can change incision, aggradation rates, which decreases channel stability until new equilibrium is reached. A big fire or storm could create unstable conditions for a few years. • Increase in flow, increase in sediment supply can lead to increased meandering and likelihood of convulsing (cutting off), meaning less stable channels. • Receding glaciers→more loose, erodible materials, steep channel gradients, so could decrease stability. Tim Abbey paper on this from late 2000s? • Increased forest fires means increased runoff, sediment for some period of time