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Independent Peer Review of the Estuary Study Portion of the 1999 Duke Engineering "Final Technical Report: Lower Skagit River Instream Flow Studies"

Prepared for the Washington State Joint Legislative Task Force on Water Supply

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

This peer review of the estuary study portion of the Duke Engineering report was produced by an expert committee convened by the Washington State Academy of Sciences for the Washington State Joint Legislative Task Force on Water Supply.

Section I is a peer review of the 1999 Duke Estuary Study, which is Section 3 of the "Final Technical Report: Lower Skagit River Instream Flow Studies" report published by Duke Engineering in June 1999. The stated objectives of the overall Technical Report were to "provide instream flow technical data...for use in the discussion and establishment of Lower Skagit River instream flow recommendations."

The purpose of Section I is to review the objectives, methods, and results of the estuary portion of the Duke Engineering Report. The estuary study includes field data collection, multiple regression modeling, and analysis of changes in river discharge on inundation of the estuary. Unusually for its time, the Duke study did well in recognizing the importance of the estuary and its links to freshwater inputs. However, the committee's peer review revealed several issues with the study's methods, including:

- The two study sites selected for tidal period habitat analysis do not capture the variability across the Skagit estuary in the influence of tides and non-tidal residuals. In addition, water surface elevations were related to estimated tidal variability at a nearby site on Whidbey Island and not at the Skagit River delta.
- While data for the study period were collected between April and November, tidal period habitat analysis was conducted using a February to August time period and the analysis was averaged over this time period to develop a single recommended flow level. The study did not report the error caused by averaging or by using different months for data collection and analysis.
- The February-August time period used in the study for tidal period habitat analysis excludes winter months that would likely have higher flow and non-tidal residuals such as storm surge, and other processes that contribute to inundation and thus habitat.
- The study used multiple linear regression analysis to describe the relationship between water surface elevation and discharge, which is not generally expected to be a linear function. Linear regression analysis does not capture the influence of nonlinear tidal, flow, and non-tidal residual processes.
- The study does not effectively address error and uncertainty; for example, instrument accuracies are not propagated through the analysis, errors associated with averaging are not reported, and extrapolations outside the range of data have inadequately reported uncertainty.
- The study is unable to capture the duration of lower-flow conditions, given the use of 10,000 cfs as a threshold condition. The study also did not estimate inundated area, which is a major weakness, and tidal variation was not included in estimates of overland flow.
- Salinity was not considered in this study, despite being a critical habitat factor.

- The study does not estimate abundance of habitat in channels or overbank areas, nor does it differentiate between fish species. This is likely because there was much less species-specific information about fish habitat available at the time of the study.

Section II is a review of the current state of methodologies, techniques, technologies, and datasets that would be employed if an estuary study was conducted today. The purpose of the review in Section II is to inform the Washington State Legislature and stakeholders on the Joint Legislative Task Force about the current state of science in evaluating estuarine flow.

The committee has several suggestions for scientific and technical approaches in a current-day estuary study (current tools that were not available in 1999 are referred to as "new") that would provide the data that decision-makers would need to assess water quality and quantity:

- Establish a study objective to prioritize study assumptions and tradeoffs.
- Account for changing habitats and environmental conditions, such as sedimentation, natural interannual variability in climatic factors, the influences of land-use changes including flow control structures (levees, tide-gates) and dams, and climate-change-induced changes in sea levels, precipitation, air temperature, snowmelt, and water quality. The committee cautions against using a single year's data to extrapolate water quality and quantity over multiple decades.
- Select additional study sites to target water quality and habitat characteristics under-represented in the Duke study.
- Connect the upstream and estuary study to better understand the watershed as a whole, particularly in the context of fish habitat and life histories.
- Use new remote sensing and mapping tools to resolve the topography, inundation, and usable habitat sufficient for species of concern.
- Use new instruments to record water quality with sensors at multiple locations in the estuary, over a longer interval of time than the Duke study to characterize the variability important to species and life-histories using the system.
- Reference land surface and water elevation to datums of concern across sectors.
- Assess conditions at finer timescales than in the Duke study: low-flow conditions at a monthly or seasonal timescale, temperature and salinity ideally subdaily/daily, monthly, or at minimum seasonally, and hydrologic changes subdaily/daily.
- Include additional analyses of the interactions between water surface elevations and inundation and flow processes, to understand the effect of inundation processes on estuary food web and species-specific fish habitat.
- Fully quantify sources and magnitudes of error and how they propagate through the analyses.
- Apply the current species-specific understanding of how salmonids and rearing marine fishes use estuary areas and include fish species that are missing from the Duke study.
- Use current modeling tools, such as: (a) a physics-based spatially-distributed hydrologic model to inform estimates of climate change and other changing impacts on streamflow and inundation in the Skagit River Basin; (b) a three-dimensional numerical hydrodynamic model to

provide a precise inundation map of the lower Skagit River; and (c) an ecogeomorphic model to elucidate the effects of flow on habitat. The committee notes that setting a single flow number for an entire year does not effectively use the detail provided by new modeling tools.

In summary, while the Duke Estuary Study took several thoughtful approaches and represents a body of work that was relatively comprehensive given the tools available when it was conducted, and the likely potential budget and management constraints placed upon the study, there are several issues with the study's methods. A current-day estuary study could use several new tools and technologies, and would be positioned to apply an updated understanding of climatic processes, habitat, and other relevant fields.

INTERPRETATION OF CHARGE

The Washington State Joint Legislative Task Force (JLTF) on Water Supply requested that the Washington State Academy of Sciences (WSAS) conduct an independent peer review of the estuary portion of a 1999 Duke Engineering Report that was commissioned by Skagit County Public Utility District No. 1 and the City of Anacortes for use by the Skagit River Instream Flow Committee to inform the 2001 Skagit River Instream Flow Rule. The estuary study's objectives, methods, and results have not been peer reviewed previously.

In response, WSAS convened a six-member committee of disciplinary experts (referred to in this document as "the committee") with the charge to conduct an independent peer review. The scope of work for this peer review was finalized with feedback from Task Force subcommittee members before the committee began its work. The full Scope of Work is provided in Appendix A.

The committee performed its review between May 2020 and January 2021. Committee members are listed in the front matter and their full bios are in Appendix B.

The Duke Engineering Report estuary study, which is the subject of this peer review, includes field data collection, multiple regression modeling, and analysis of changes in river discharge on inundation of the estuary. The remainder of the Duke Engineering report, which provided additional context for our peer review, includes an introduction, main river instream flow study, a hydrology study, and discussion and recommendations. The committee notes that the Appendices referenced throughout the report were not available. Efforts by Ecology staff to find those appendices were unsuccessful.

The committee's review includes two sections. Section I is a peer review of the Duke Estuary Study. Cited section numbers correspond to those in the Duke Engineering Report. Section II is a review of the current state of methodologies, techniques, and datasets (including new or improved knowledge of estuaries and species since 1999) that would be employed if an estuary study was conducted today. Questions from the Scope of Work are addressed in the text; however, the question "What is the management reference point – that is, the baseline standard for comparison – for ecological risk in this river/estuary system?" could not be answered, as "ecological risk" and "baseline" would both need to be defined before this question could be answered, and the question is more policy-focused than science-focused. The purpose of the review in Section II is to inform the Washington State Legislature and stakeholders on the Joint Legislative Task Force about the current state of science in evaluating estuarine flow.

I. REVIEW OF THE DUKE ESTUARY STUDY

This chapter aims to review the Duke Estuary Study, which is Section 3 of the "Final Technical Report: Lower Skagit River Instream Flow Studies" report published by Duke Engineering in June 1999, and the advantages and limitations of the study's methods.

The stated objectives of the entire Final Technical Report were to “provide instream flow technical data...for use in the discussion and establishment of Lower Skagit River instream flow recommendations...The study primarily focused on the habitat needs of important salmonid species that use the Lower Skagit River for all or part of their fresh water life cycle." [page 2 of the report] The stated objectives of Section 3, the estuary study portion of the report that this committee was tasked to review, were “ a) to spatially and temporally isolate the tidal from the non-tidal periods; b) to establish a relationship between freshwater discharge and Water Surface Elevation (WSE) for selected estuary channels and associated tidal marshes during both tidal and non-tidal periods; and, c) using WSE as the link, to model estuary hydrodynamics and potential salmonid habitat availability as a function river discharge.” [page 43 of the report]

Unusually for its time, the Duke study did well in recognizing the importance of the estuary and its links to freshwater inputs. However, across the report, the assumptions that were made were not clearly stated upfront, and in some cases the justifications were absent or unclear. Assumptions and uncertainties are inherent in research studies, and it is good practice to provide justifications for any choices made.

Watershed site selection

The Duke Estuary Study report indicates that the study sites were chosen to be “generally representative of the mixture of channel types and sizes in the estuary”. Fifteen study sites were identified to represent lower, middle and upper zones in the estuary of the Skagit. Sites within these zones had different characteristics of channel morphology, overbank flow potential, and influence of freshwater. The 15 sites initially chosen likely represent the diversity of flows and responsiveness of the estuary to tidal and non-tidal influences.

Only two of the 15 sites (representing a total of 3 transects) were used as part of the tidal period habitat analysis – Deepwater Blind Slough (DWB) and North Fork Blind Slough (NFB). These two sites are in the middle reaches of the estuary, affected by tides and discharge, and have the possibility of overbank flooding events. However, the two sites examined do not capture the variability across the Skagit estuary in the propagation and influence of tides and non-tidal residuals (NTRs) upstream and across estuaries, which are controlled by the amplitude and phasing of the tide wave and storm surge, stream flow, estuary topography, and complexity (roughness).

Given these issues, it would have been more useful for analysis of tidal period habitat to have included a larger number of sites with overbank possibilities, in order to get a better coverage of the estuary and understanding of flooded and hence usable area for relevant fish species and life-cycle stages. In addition, the analysis used the average of the duration of inundation data in both sites and ignored any differences between the sites.

Data collection and use

Pressure transducers were deployed at each of these sites for two-week intervals in a rotation pattern in order to capture river discharge and site-specific responsiveness to tidal influence. WSE data were measured and the multiple linear regressions between WSE and discharge or tide level were developed for these sites.

Water surface elevations were related to estimated tidal variability at a nearby site on Whidbey Island and not at the Skagit River delta; Whidbey Island may be different in magnitude and phasing from the study site. The derived relationships between water surface elevation in the delta to offshore tides offer advantages for long-term forecasts but likely misrepresent actual relationships that are influenced by storm surge and other non-tidal processes excluded from this study but that influence water levels. High water periods, in addition to low water level periods, are important contributors to the habitat. In addition, streamflow was measured at the Mt. Vernon gage in the main stem, but this measurement location does not account for the differences in sedimentation over time along the mainstem and north and south forks of the river, which alter streamflow and stage.

While data for the study period were collected between April and November, tidal period habitat analysis was conducted using a February to August time period, based on the assumption that this was the time of year when most salmonid rearing occurred in the estuary. Data over this time period were ultimately averaged in order to develop a single recommended flow level for the entire seven-month analysis period. The analysis was averaged over this time period, but the study did not report the error created by averaging.

Excluding winter from the analysis is also a problem for understanding the needs of other life stages of fishes, due to winter drops in salinity (more in *Water quality*). In addition, it is unclear whether the year in which the study was conducted was representative of all years.

The February to August time period for analysis was also a limitation in the study's assessments of overland flow, which would be more likely to occur during higher-flow winter months that were not part of the time period of assessment. It is unclear if other sites would have been part of the tidal period habitat analysis if winter flow conditions were included in the assessment. In addition, NTRs like storm surge elevate surface water 1 to 3 feet above tides in the winter months (October to April). These are not included or considered in the estuary study. The exclusion of winter months also minimizes processes that contribute to inundation, and thus habitat, affecting the error of the analysis.

Remote sensing, sensor networks, and techniques

Pressure transducers were the only sensors implemented in the study. They were used to determine water surface elevation, but only two sets were deployed and had to be rotated between sites every 2 to 3 weeks because of their cost. Additional sensors would have provided a more robust assessment of flow conditions.

An acoustic doppler current profiler (ADCP) was used to measure cross-sectional profile in the main channels where depths were greater than 1.5 feet. For the shallow channels where depths were less than 1.5 feet, direct measurements were used since ADCP was not feasible. This study did not use satellite or aerial remote sensing to complement the in-situ measurements for characterizing water surface elevation (more in *Part II - Remote sensing*).

Water level and tidal issues

Linear regression analysis

In the estuary study, multiple linear regression analysis was used to describe the relationship between water surface elevation and discharge and/or tide. The use of linear regression analysis is questionable because in principle one would not expect water elevation to be a linear function of discharge or the compound influence of river flow and tide across the area of concern.

A linear regression analysis does not capture the influence of nonlinear processes. Surface water elevation and tidal inundation (extent, frequency, etc.) are controlled by tides, stream flow, and NTR processes (storm surge, inverse barometer effect, winds and wave setup), and processes operating outside of the Salish Sea that propagate into and across the study area, such as wind stress and inter-annual to decadal temperature anomalies. NTR anomalies can reach 3 ft, with the greatest anomalies most commonly occurring between November and April, and persisting for multiple days. Though the flooding time period is short, the habitat is in part shaped by flooding processes, affecting how fish and other animals can use the additional habitat for that period or in other time periods. NTRs increase the likelihood of intersecting high tides and high stream flows that lead to inundation, habitat formation/maintenance, and habitat use.

Even considering the fact that this study obtained the discharge from one location (i.e., near Mt. Vernon) and WSE from each of the 15 selected sites in the estuary, it is doubtful whether the use of multiple linear regression was reasonable. In addition, standard errors are not reported for the regressions.

Error and uncertainty

The Duke estuary study doesn’t effectively address the error and uncertainty in the study approach. Accuracies are given for each measuring instrument but are not propagated through the later analysis. The study also does not discuss the practical issues that would make actual accuracy poorer than the accuracy claimed for the instrument. For example, in overbank areas the presence of vegetation would have made it difficult to define the surface whose elevation was actually being measured.

As mentioned previously, the estimated duration of inundation in the estuary, data on discharge, tides, weather, and site WSE were averaged over the collection period of April to September and applied to analysis of February to August conditions. The possible uncertainty stemming from using average flows from one set of months to estimate another set was not addressed.

Average values were also used in the habitat assessment and final recommendations for flows (Table 3.6-3), but again, no measures of the errors and uncertainties associated with those averages were presented. Averaging over the three transects in the middle section of the estuary is likely to lead to significant uncertainties. In the final analysis it is inaccurate to quote results in Table 5.3-1 to three significant digits (e.g., "843 cfs") given the uncertainties involved.

The study also makes references to extrapolations outside the range of the data, which would have greater uncertainties than standard errors of estimate, and does not clearly represent the variation associated with the extrapolations.

However, the uncertainty regarding the above-mentioned measurements is dominated by limitations of the data, time sampling issues, and how well the data presented represents the true hydrodynamic conditions.

Joint probabilities of tide and river flow

The Duke Study was thoughtful in the approach used to distinguish between tide and river flow to predict water surface elevation, accounting appropriately for the joint probabilities of tide and river flow. Tide data from NOAA and streamflow data from the long-term USGS gage at Mt. Vernon are strong datasets that were foundational in determining tide and river flow relationships. The approach to addressing tides is determined by the availability of gaging. The Duke Study removed data during periods of strong southerly winds, which helps to account for the lack of availability of gaging.

It is unclear if the final flow recommendations are reasonable because the error is not reported. In addition, as previously mentioned, the study's depiction of a linear relationship with water surface elevation over the period of April to November does not capture the variability that shapes habitat and habitat accessibility.

Ideally, the Duke study would have measured the recommended flows each month and compared the monthly values with the single average value to account for the uncertainty of the use of the single value. The monthly recommended flow could have been summarized into more meaningful periods such as low flow season vs. no-low-flow season, and this type of assessment of seasonal flow conditions would have been more informative for an assessment of low-flow conditions.

Evaluation of low-flow conditions

This study makes several decisions that make evaluation of low-flow rates problematic, including that seven months of collected duration data were averaged and used to provide a single recommended flow rather than a recommended flow for each month.

Capturing the duration of lower flow conditions is not possible with the current analysis that used 10,000 cfs as a threshold condition. Several sites appear to have thalweg (the line of lowest elevation along the course of a river) depth of 1 foot (with little supporting evidence for why this threshold was chosen), indicating that they would provide habitat at lower flow levels (Table 3.6-2). Among all of the sites, only DWB and NFB were considered in calculating the average values. The Duke study did not account for the uncertainty that resulted from using the average of two sites to represent the whole estuary, even if it captures the conditions in the middle portion of the estuary at the chosen transects.

Evaluation of statistical availability of overbank habitat

The Duke study did not model elevation and flow levels, which would have given an assessment of overland flow and inundation. In addition, averaging over seven months makes it impossible to address the duration of overbank events. This lack of any estimate of inundated area is a major weakness compared to the upstream study's reporting of weighted usable area (WUA).

Table 3.6-2 captures flow levels at which habitat (defined as 1 foot thalweg depth) for fishes would be available. Knowledge of when such habitat is available would be informative, due to the seasonal nature of fish use of estuary areas and floodplains for rearing.

Water quality, including salinity

Salinity is an important factor that affects vegetation, wetlands, and how fishes use the habitat. Salinity was not considered in this study, beyond a relatively simple assessment early in the descriptive part of the report describing the estuary as a salt-wedge estuary due to the dominance of river flow and relatively limited mixing of fresh and saltwater. The report also mentioned an elevated sandbar that may restrict saltwater intrusion deeper into the estuary and that may also modify tidal drainage patterns.

Measurements of the salinity wedge, seasonal variability in salt intrusion, and interactions between high and low river discharge with salinity were not discussed in the report. Tidal variation was not included in estimates of overland flow, which interacts with salinity and may have been particularly relevant in the lower portion of the estuary with the most direct interaction with marine cycles.

Fish ecology and habitat

The Duke estuary study does not differentiate between fish species, or include much relevant information about food-web processes. In addition, abundance of habitat was not estimated in channels or overbank areas.

When this study was completed, there was less specific information available about how individual species of salmon, trout, lamprey, and other fishes use estuary areas. For example, Coho salmon were not mentioned in the report. Other estuary-rearing marine fishes were discussed in the introduction, but were not included in later analysis of flow.

Based on the information available at the time, the general approach to fish habitat designation was a good fit that was broad enough to encompass elements of estuary rearing for native salmonids. In the time since the Duke study was conducted, there have been significant improvements in knowledge of the multiple life-history uses of different habitats by different salmon species and their prey through time (more in *Part II - Fish ecology and habitat*).

Modeling tools and applications

The Duke study did not include any detailed modeling. Seasonal and monthly variability is not addressed in the report, as data collection did not encompass the entire year, and collected data were averaged over the time period of interest. Discharge and tides vary on an hourly basis. In the opinion of the committee, a biweekly (Spring-Neap tide cycle, specifically) analysis would be ideal to address variations in fish habitat, and the coarsest scale that would be sufficient would be seasonal, in order to capture seasonal variability in tidal and non-tidal flow patterns. Although the regression analyses are described as a “model”, it is a stretch to describe them as such.

Summary

In reviewing the estuary study portion of the 1999 Duke Engineering Report, the committee finds that, while the study did well in recognizing the importance of the estuary and its links to freshwater inputs, there were several issues with the study’s methods. In particular, the methods used in watershed site selection, data collection and use, water level and tidal data analysis and evaluation of low-flow conditions, measures of water quality, evaluation of fish ecology and habitat, and modeling were lacking.

II. CURRENT-DAY ESTUARY STUDY

This chapter aims to outline the scientific and technical approaches to provide the data that current-day decision-makers would need to assess water quality and quantity in an estuary study.

First and foremost, establishing a study objective would be a key prerequisite to any current-day estuary study. The study objective is not only a policy question, but also a scientific question, as it informs relative prioritization of the many assumptions and tradeoffs inherent in a study. This committee cannot dictate what an appropriate study objective would be, but questions that would help to set a study objective might include: What level of certainty about flow condition is needed? For what time period should the study's flow estimate be valid (multiple seasons, multiple years, etc.)? How precise does the water depth in channels need to be to answer questions about habitat? Is there a need to understand river and tidal flow and inundation in a diversity of channel sizes (widths and depths)?

Changing habitats and environmental conditions

Management decisions need to include an aspect of changes over time, as habitats and environmental conditions are not static. Although many of these changes occur on a long timescale, the following processes have affected water quality and quantity in the Skagit Basin estuary even in the period since 1999.

Sedimentation and tectonics

Over time, sedimentation has modified the estuary and channels. In the last 50 years, including the time period since the Duke Study, there has been sedimentation of 3-10 feet in the mainstem river channel in and around Mt. Vernon, with the largest change in the lower river and estuary [Grossman et al. 2020]. Sedimentation leads to a complex patchwork of changes in the river and estuary morphology and elevation relative to sea level over time [Kairis & Rybczyk 2010], which in turn affects channel depths, water flow, temperature, and salinity.

Tectonics can affect the landscape through uplift and deep subsidence, but the committee does not expect the Skagit Basin landscape to be highly affected by tectonics, barring a major tectonic event such as an earthquake [Miller et al. 2018].

Interannual variability

Climatic factors that affect water availability, such as air temperature, precipitation patterns, storm surge, wind speeds and directions, and so on differ from year to year and on decadal scales. Thus, the committee cautions against using a single year's data to extrapolate water quality and quantity over multiple decades.

Climate change impacts

Researchers' understanding of the various processes of climate change and their effects on the Skagit Basin has changed since the Duke estuary study was completed. Accounting for climate change would be an important component of a current-day estuary study. These effects of climate change include changes in the magnitude, timing, and frequency of several environmental processes that impact estuarine habitat, including:

- **Rising sea levels:** Sea-level rise will have an impact on inundation in the near-coastal area [Miller et al. 2018], and increased winter streamflow with sea-level rise will affect the entire floodplain in the lower parts of the Skagit watershed [Hamman et al. 2016].
- **Increased impacts of storm surge:** Sea level rise can exacerbate the impacts of storm surge, which can lead to increases in estuarine flooding.
- **Higher air temperature:** The literature indicates a near future (2006-2035) annual temperature increase of approximately 2-4°F and summer temperature increase up to 5°F [Bandaragoda et al. 2015]. Warmer summers and winters may lead to more hydrologic extreme events such as winter floods and summer low flows. Warmer summer air temperature, compounded with lower summer flows, are likely to increase summer water temperature.
- **Changes in phase of precipitation:** Climate change is expected to result in more precipitation arriving as rainfall (water that is immediately present and runs off) and less as snow (which essentially stores water and leads to later, more continuous water releases). This change in type of precipitation will affect freshwater hydrology.
- **Changes in snowmelt:** Reduction of peak water storage in the snowpack and changes in magnitude and timing of snowmelt propagate to the hydrograph. It is expected that winter flood peaks will increase and the timeframe of high flows will be extended [Bandaragoda et al. 2015; Lee & Hamlet 2011]. Low summer flows are projected to be lower in the future, with differences in the extent based on elevation [Bandaragoda et al. 2015; Stumbaugh & Hamlet 2016].
- **Shrinkage of glaciers:** Glaciers have been retreating due to observed warming since the 1970's [Riedel & Larrabee 2011] and glacial retreat is likely to accelerate in response to projected warming [Bandaragoda et al. 2015; Chennault 2004]. Reduction of the extent of glacial area is expected to result in exacerbated summer low flows and higher summer water temperature [Mantua et al. 2010].
- **Changing water quality:** More extreme water temperature and salinity, occurring both directly from warming ocean and estuary water, and indirectly from precipitation changes, change habitat quality.

The above-mentioned effects of climate change impact estuarine habitat. Exacerbated summer low flows and more extreme water temperature and salinity reduce available habitat and impose more stress on cold water fish species that use estuary areas for rearing [Austin et al. 2020].

Land use changes

Land use changes are also likely to affect the estuary – in particular, as a result of levees and tide gates in lowland areas. Tide gates are barriers that keep saltwater out, leading to accumulation of fresh water upstream of the tide gate. Tide gates create differences in temperature and salinity on the two sides of the gate, which may limit movement possibilities for migrating species such as coho salmon [Bass 2010]. These differentials may especially be an issue in summers when low winter precipitation leads to lower flow conditions. Levee breaches can cause lasting changes in estuaries as there is more flooding in the area.

Dams in the Skagit River watershed influence daily streamflow, water temperature, and turbidity of water flowing into the estuary throughout the year. For example, dam operations have successfully reduced peaks in the lower portion of the Skagit River and the estuary. However, dams would not effectively control peak flows under climate change because there would be substantial increase in winter peak flows in the Sauk River, which is a tributary that is not dammed [Lee et al. 2016]. Thus, the effect of these dam-influenced changes on hydrology and consequently on habitat availability across the estuary would be important to include in future studies.

Other land use changes may occur as a result of changes in population distribution, groundwater pumping, changes in agricultural practices, new industries, and so on.

Watershed site selection

In a current-day study, it would be ideal to select sites in addition to those from the original study to enhance rigor and to target specific flow characteristics that were under-represented in this dataset. This includes densifying the sample sites in the middle zone and emphasizing sites that have overbank potential (*Figs 11 & 12 in* [Hamman et al. 2016]), including some of the smaller estuary channels. Looking across areas of the estuary rather than just at overbank middle-zone sites would also enhance comparisons of the effect of non-tidal flows, and interactions between tidal and non-tidal flows (i.e., transects with overland flow). In addition, new modeling tools (more in *Modeling*) would address conditions across the entire landscape, rather than only at specific sites.

It would be reasonable to select additional study sites based on the current understanding of habitat use by different life stages of salmon (more in *Fish ecology and habitat*). While in practice research is almost always separated between upstream and estuary studies, an integrated assessment that spans both bodies of water is critical to understanding the watershed as a whole, as well as salmonid life history.

Regardless of the sites chosen, all data collection and analyses should be conducted over the same time period to characterize variability and minimize error.

Remote sensing, sensor networks, and techniques

Mapping tools

Remote sensing, and in particular airborne LiDAR can be used to create a detailed, fine-resolution topographic surface, commonly referred to as “bare earth” model [Dong & Chen 2017]. Both topographic LiDAR flown at low tide and bathymetric (blue-green laser) that penetrates the water column (where sufficiently clear or minimal turbidity) can resolve the surface elevations, morphology, and vegetation characteristics [Tyler et al. 2020] important to assessing the land surface subject to inundation and usable area of fish activities. Current hydrodynamic models use LiDAR to survey overbank and in-water bathymetric conditions and define cross sections in the model [Mauger & Lee 2014].

Bare earth models derived from LiDAR can be biased by vegetation and require additional information and data processing to remove its influence on flooding of wetland surfaces and channels. RTK (real-time kinematic) GPS mapping of areas of dense wetland vegetation is commonly used to quantify the canopy height and cover of vegetation to make these bias corrections; other methods are also available [Buffington et al. 2016]. Ideally, LiDAR data collection targeted for this purpose is collected during low-growth or senescent times for vegetation, such as winter, and at low-tide, to reduce the effect of vegetation height and density as well as tidal inundation on data collection.

Bathymetric LiDAR could be used to define cross sections, rather than other intensive approaches (leveling surveys, ADCP) that was used to characterize the channel cross-sections deeper than 1.5 feet in the Duke study. Bathymetric LiDAR suffers from turbidity and technical elements (e.g., blanking distance near the water surface) that need to be considered to resolve elevations and depth. Therefore, it is best used in conjunction with other standard approaches (e.g., sonar) in sediment rich streams like the Skagit.

While LiDAR measurement is ideal, it can be expensive. This investment can be leveraged by collecting complementary data for other uses, as long as the critical measures (tide, vegetation, etc.) are accounted for. Optical remote sensing from drones including Structure-from-Motion photogrammetry [Carrivick et al. 2016] are improving for mapping topography and bathymetry during low water, and for mapping vegetation. They also are efficient for mapping inundation, are less intensive and expensive than LiDAR, and can capture similarly helpful transect measurements.

Water-quality sensors

New tools including updated pressure transducers to measure water depth, conductivity meters to capture salinity, and temperature loggers to record temperature are now available and could record water quality in multiple locations in the estuary. These instruments are more affordable than they were in the past and can be safely deployed for extended periods of time. Also, Bluetooth technology allows for simpler and easier download capabilities than was the case in the past. Additional pressure transducers deployed for longer intervals of time than in the Duke study would also improve future work.

Water quality, including salinity

A current-day study would include the primary water quality factors of temperature, salinity, and dissolved oxygen as environmental metrics of interest. Fluctuations in salinity and temperature associated with tidal cycles are particularly pronounced where tide-gates are present, and may introduce variability in water quality for fishes, particularly during the summer when flow is lower and salinity may be higher (due to less dilution from river discharge). Thus, finer timescales would be important for assessing temperature and salinity. Temperature and salinity would ideally be reported daily or subdaily, and if not possible then monthly, and at a very minimum seasonally.

Pollutants from runoff (i.e., roads [Tian et al. 2021]) could also be relevant to consider from the estuary perspective, particularly as the low flow conditions in summer may exacerbate pollutant concentration in estuaries and are projected to be more prevalent in the future.

Water level and tidal issues

Available data

Available data characterizing water levels across the estuary through time can be derived from direct measurements or the outputs of validated models. Direct measurements of water levels have been made continuously at the USGS Mount Vernon stream gage [USGS 2021] but few known published data sets, if any, exist in the estuary (area of concern to project) and span more than a few months.

In order for a current-day study to accurately represent temporal and spatial variability in water levels across estuaries, empirical data at the resolution and extent required by the study objective would be used directly if located at enough sites, or to validate models (more in *Modeling*) that can predict water levels where needed. Given the dynamic nature of the Skagit estuary, such models will likely be representative for discrete amounts of time until conditions change and will be most useful if they can be updated periodically to represent water levels, flows, and other factors that will change with changing conditions.

Timescales

In a current-day study, flow conditions would need to be assessed on a finer timescale than in the Duke study. For example, low-flow conditions would have been better informed by a monthly or even seasonal assessment of seasonal flow conditions than an average over seven months. New designations important to the species of concern which have been introduced since the Duke report include 7Q10, the minimum 7-day average flow that occurs once every 10 years (on average). Hydrologic changes occur on a daily or sub-daily basis, dominated by precipitation and snow processes, especially in headwaters.

A current-day study would need to develop a clear understanding of the influence of low-flow conditions, which can occur on very fine timescales (hours, days, etc.) and which can have very different effects dependent on location in the watershed and bathymetry, shading, and groundwater conditions. Data used for a current-day model would need to use subdaily or mean daily flows (likely from USGS data).

Analyses and error

Since the Duke report was completed, there have been significant increases in the understanding of water surface elevations, inundation and flow processes, and their complex interactions. A present-day study would likely include additional analyses such as exploring relationships with water-surface elevation based on multiple sites within the upper, middle, and lower portions of the estuary. A current-day study would also describe or define relationships between tidal height and occurrence of different species of fishes or the estuary food web, which is not addressed in the Duke study.

Importantly, since the Duke study was conducted, the research community's understanding of and ability to quantify the various sources and magnitudes of error have greatly improved with improved mapping and sampling approaches. Error and uncertainty in maps and geospatial data generally are now recognized as especially problematic, but significant advances have been made in the relevant theory and in the propagation of uncertainty during analysis and modeling [Heuvelink 1998; Zhang & Goodchild 2002].

Fish ecology and habitat

The understanding of how salmonids and rearing marine fishes use estuary areas has improved considerably since the Duke study was conducted. Recent decades have seen increased understanding of the relationships between many species of native fishes and estuaries, fish habitat use, life history diversity, and the variability in organisms' tolerance and resilience to varying conditions.

In particular, the science linking life history diversity of Chinook and Coho salmon to the availability of estuary habitats is evident in otolith analysis, as well as in growth rates of juvenile fishes in estuaries where their use of estuaries throughout the winter months has been documented [Bieber 2005; Bottom, Jones, et al. 2005; Cornwell et al. 2001; Hering et al. 2010; Jones et al. 2014; Miller & Sadro 2003; Volk et al. 2010]. The importance of habitats at the intersection between fresh and saltwater has also been demonstrated in the literature with strong juvenile behavioral diversity in Coho [Weybright & Giannico 2018] and Chinook salmon [Bottom, Jones, et al. 2005]. The literature also shows [Nordholm 2014] that juvenile Coho salmon that use estuaries for rearing ultimately contribute disproportionately to the returning population of adult spawners.

Marine survival of anadromous trout (e.g. Steelhead trout [Bond et al. 2008]) and juvenile rearing [Bond et al. 2008; Hayes et al. 2008] has also been shown to benefit from access and use of estuary habitats. Other research indicates that declines in estuary conditions are linked to the decline of salmon at the population-scale (i.e., Columbia River Chinook [Bottom, Simenstad, et al. 2005]). Research in more recent decades also points to the importance of small channels in providing important terrestrial food sources for fishes [Gray et al. 2002]. A more well-rounded understanding of the variety of channel configurations found in estuaries indicates that overbank flow is not the only habitat of importance for fishes.

Fish species missing from the Duke Report that may be of interest in an assessment of species-specific estuary habitat needs include Pacific Lamprey, who are known to be distributed in the Skagit River watershed and are important to the ecosystem.

While fish habitat would likely be the key focus of a current-day estuary study, it may be helpful to consider other wildlife that support the ecosystem. For example, beavers are ecosystem engineers who can occupy lowland habitat and are known to develop important rearing habitats for salmonids [Pollock et al. 2004]. Other species of conservation interest that rely on estuaries include migratory and resident species of birds (e.g. shorebirds, waterfowl, corvids, raptors [Frazier et al. 2014]), and mammals (e.g. otter, ungulates or rodents [Callaway et al. 2012]).

Modeling and data analysis tools and applications

Modeling capability, computational time and cost, accessibility, accuracy, calibration, and spatio-temporal resolution have all improved considerably since 1999. It is important to note that the nuance and detail afforded by all of these tools is most relevant in a management context that allows for higher temporal resolution - that is, setting a single flow number for an entire year does not effectively use the detail provided by new modeling tools.

The types of models described below are already in use, with existing models that have been initialized, calibrated, and validated, and for which simulations have been run in the Skagit. For these models, much of the input data already exist, but some revised inputs such as updated bathymetry and water level data would improve and reduce uncertainty in their outputs. In addition, given the dynamic nature of the Skagit estuary, models will be most useful if they can be updated periodically to represent water levels, flows, and other factors that will change with changing conditions.

Challenges with models include cost, computational resources, expertise, extensive data needs for calibration and validation, environmental variability and representing the dynamic and frequent changes that the system undergoes. With increased complexity and resolution, considerable effort, time, and expertise is typically required to collect input data, set up, calibrate, and use models. Much of this upfront effort has already taken place in the Skagit Basin through previous model applications, although a high level of expertise is generally required to maintain and run the models. Study objectives and the questions of concern should be considered when deciding if the use of a complex model is justified. That said, the tools mentioned in the following subsections have been selected because, on balance, their advantages outweigh their limitations.

Hydrologic and simulation models

A hydrologic model of the Skagit Basin was not included in the Duke study, which instead used gage-measured regulated streamflow at Mount Vernon. A physics-based, spatially-distributed hydrologic model would be appropriate to use for an estuary study, given current computing and modeling tools. Outputs from a hydrologic model and then a simulation model would inform the hydrodynamic model which could estimate inundation in the estuary and lower portion of the Skagit River.

For example, a meso-scale hydrologic model has been used to estimate the climate change impacts on streamflow for the Skagit watershed [Hamlet et al. 2013; Lee et al. 2016] and outputs from the hydrologic model were then used to force a simulation model to estimate the influence of dam operation in hydrology [Lee et al. 2016]. Then the outputs from the simulation model were used to force the hydrodynamic model to estimate water levels in the estuary and lower portions of the Skagit River [Hamman et al. 2016]. The committee is also aware of studies that applied a coupled glacio-hydrology model to study the climate change impacts on glaciation, hydrology, and/or water temperature in the Skagit River Basin [Bandaragoda et al. 2015, 2019]. The studies used the Distributed Hydrology Soil Vegetation Model (DHSVM), which is a finer-scale hydrologic model [Frans 2015; Naz et al. 2014; Wigmosta et al. 1994] to simulate streamflow throughout the channel network.

A high-resolution model can be used in conjunction with observations to provide streamflow estimates where and when observational data are not available. This type of model is a viable method to consider the impact of future conditions (climate, land use, etc.), as most statistical methods based on current observations assume “physical constancy of mechanisms participating in the formation of streamflow,” which is unrealistic due to substantial anthropogenic changes to the Earth’s climate [Klemeš 1989; Milly et al. 2008]. Ensemble-based simulations, in which multiple models or variations of model parameters are used, can help to address uncertainty in models and current/future climate conditions.

Hydrodynamic models

A three-dimensional numerical hydrodynamic model of the estuary and lower portions of the North and South Forks of the Skagit River was not included in the Duke study, but is likely important to achieve its goals, given the complexity and high spatiotemporal variability of the system and current computing capabilities.

The committee is aware of multiple hydrodynamic models applicable to the Skagit River estuary, including one led by Pacific Northwest National Laboratory [Khangaonkar et al. 2019] and the U.S. Geological Survey Puget Sound Coastal Storm Modeling System (CoSMoS) [Tehranirad et al. n.d.]. Hydrodynamic models have been used for the areas downstream of the Skagit [Hamman et al. 2016] and the Snohomish [Mauger & Lee 2014; Nugraha & Khangaonkar 2018] rivers to estimate inundation in the watersheds due to streamflow (or discharge), tidal flow and sea level rise.

An informative 3D hydrodynamic model of the estuary would incorporate several parameters and updated data, and thus comprehensively and accurately represent boundary conditions and provide needed information for validation. The resolution and accuracy of these data would vary for stated objectives of the water quantity, quality and associated habitat suitability goals. Updated boundary condition and validation include detailed topographic and bathymetric data (more in *Remote sensing*), time-series measurements of water levels across the estuary, marine water levels in Skagit Bay nearby, and river discharge at the landward discharge boundary, Some questions require measurements of current velocity, suspended sediment concentration (or turbidity as a surrogate), salinity and perhaps other water quality parameters affecting habitat suitability (pH, nutrients, contaminants).

In addition, the model would need to include sediment transport processes to address the influence of changes in sediment inputs and fluxes through the lower river and estuary that have immediate and long lasting effects on water levels, currents, water quality (temperature, salinity, and turbidity) and are strongly responsive to land use activities [Grossman et al. 2020] and climate changes [Lee et al. 2016]. Better understanding how and at what rate channel/estuary morphologic change occurs in response to events operating on time scales of flood events, days, seasons, and years is needed to achieve the goals of assessing resilience in water quantity, quality and habitat suitability over years to decades.

Such a model would represent the full range of conditions that drive change in the estuary and would capture precise patterns, depth, area, and duration of inundation of floodplain and tidal channel habitats. Some of these boundary conditions are published and accessible, but change over time with sediment transport (more in *Part I - Watershed site selection*). A hydrodynamic model with precise topographical data would provide a precise inundation map in the lower portion of the Skagit River.

There is also the potential to create a digital twin [Batty 2018] of the Skagit estuary, that is, a digital representation of the estuary that is continuously maintained as a contemporary repository of the relevant models, data, and new data analyses. Similar to other modeling tools, it may be challenging to determine which entity maintains and updates any digital twin of the Skagit River estuary.

Ecogeomorphic models

Advancements in the field of ecogeomorphology since the 1999 Duke report have led to the development of a suite of numerical models that simulate the non-linear interactions and feedbacks between river flow, tides, sediment accretion and erosion, channel development, and vegetation in coastal marshes and estuaries (see [Fagherazzi et al. 2012] for a review of models and applications). In the Skagit system, these types of model have been used to predict the effects of sea level rise in eelgrass systems [Kairis & Rybczyk 2010] and carbon sequestration in the Padilla Bay National Estuarine Research Reserve [Poppe & Rybczyk 2018]. Coupled to the previously mentioned hydrodynamic models, ecogeomorphic models could potentially be used to further elucidate the effects of Skagit flow on estuarine habitat.

Data analysis

Artificial intelligence (AI) analyses could be a useful technique for mapping inundation from airborne optical remote sensing. Much progress has been made in recent years in developing the techniques of AI and machine learning in the earth sciences, and in dealing explicitly with phenomena distributed in space ("GeoAI"). Data obtained from sample sites could be interpolated using AI techniques such as neural nets, as an aid to classification of the estuary landscape and the estimation of WUA [Srivastava et al. 2017].

AI and machine learning (ML) can also be valuable tools for use in modeling, but require sufficient data in order to be applied effectively. The committee does not see a clear way of making use of AI/ML in the context of current nonlinear hydrologic models with current data availability, but these techniques could be used in the future if sufficient data and supporting information develops.

Methods used to set instream flows in tidally influenced areas in other locations

In one conceptual modeling approach, described in multiple papers [Alber 2002; Hoese 1967], the concern in determining necessary freshwater inflow values is the effect of reduced freshwater into estuaries that changes the salinity balance in the estuary. Salinity ultimately affects vegetation, biota, and associated ecosystems. Several case studies have been presented that offered different ways of determining minimum freshwater flows into estuaries based on local concerns. In one study, science and data collection focused on certain species of interest and their biological needs, to guide determination of salinity levels and freshwater inputs. In another example, freshwater flows were linked to the locations in the estuary that needed specific salinity and freshwater levels. In all of these cases, the relationship between freshwater inputs and their influence on salinity levels was critical to the determination of freshwater flows.

This contrasts with the approach taken to the determination of freshwater inflows to estuaries described by the National Academies in an evaluation of instream flow designation in Texas [National Research Council 2005]. This report references the Savannah River estuary in Georgia and explained the development of estuary freshwater inflow requirements that varied by month based on a percentage of expected river discharge.

Summary

The committee has outlined scientific and technical approaches that would be used in a current-day estuary study. A study objective would need to be established to inform scientific assumptions and tradeoffs, and a current-day study would account for changing habitats and environmental conditions, including sedimentation, interannual variability, climate change impacts, and land use changes. The committee suggests an integrated assessment that spans upstream and estuary areas, uses new mapping and water quality sensor tools, tracks water quality factors, uses finer timescales for flow conditions, quantifies error and uncertainty, uses new scientific understandings of fish ecology and habitat, and makes use of new modeling and data analysis tools. A study conducted with current-day tools and scientific understanding could provide useful data to assess water quality and quantity to inform decision-makers.

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APPENDIX A: PEER REVIEW SCOPE OF WORK

Task Description:

Dependent on the scope of work and budget refinement in Task 3, WSAS will conduct a peer review of the Duke Engineering Report estuary study and review the current state of information/methods for setting instream flows related to estuaries. The estuary portion of the Duke Study (June 1999) was part of a larger report that also included an Instream study that informed the current instream flow rule; it was never independently reviewed. Along with the abovementioned study of water supply and demand in the Skagit watershed, the goal of WSAS's independent review of the Duke Estuary Study at this point in time is to inform the Washington State Legislature and stakeholders on the Joint Legislative Task Force about the best available science to evaluate estuarine flow with current demands in mind. Specifically, the goals of the peer review of the Duke Estuary Study are twofold: first, to constructively review the 1999 study, and second to advise on the methodologies, techniques, technologies, and datasets that would be employed if this study was conducted today.

To perform this peer review, WSAS will:

1) Identify a committee of 5-7 scientific and technical experts to conduct an independent third-party peer review of the estuarine study portion of the Duke Engineering Report relative to the best standards and practices at the time. This committee will tap the Academy membership and their extensive knowledge of leading experts in Washington State and elsewhere (if needed) with the disciplinary expertise required to conduct independent peer reviews, including but not limited to the areas of hydrology, hydrogeology, fish biology, estuarine ecology, instream flow, statistical analysis, estuarine bathymetry, and field data collection techniques.

2) Prepare a written peer review of the estuary portion of the Duke Engineering Report. This will include a review of the data collection techniques, statistical analysis and modeling methodologies, as well as the assumptions and thresholds used in the study.

Specific questions to consider:

- Is the Duke Study still relevant, given changes in climate and land use in the basin and estuary over the 20+ years since its release?
- Does the Duke Study account for errors/uncertainty in estimating duration of inundation that supports the structure, function, and food web processes of the estuary under different combinations of flow and tidal conditions? Is the linear regression analysis used in the review appropriate?

    - Does the Duke Study appropriately account for joint probabilities of tide and river flow when predicting water surface elevations throughout the study reach, or for error/uncertainty that result from translating tide elevations from off-site tide stations?

    - Are the conclusions drawn regarding the significance of impacts to inundation duration supported by the analysis conducted? Specifically, does the Duke Study appropriately evaluate the importance of river flow on inundation at flow rates less than 10,000 cfs, accounting for errors/uncertainties?

- Was the abundance and utilization of habitat accounted for in the determination of significance of impacts to fish?

- Does the Duke Study include an evaluation of when overbank habitat is statistically available, given known data about tidal and riverine conditions? Did the Duke Study include a statistical evaluation of significance of river discharge and tidal flows to duration of overbank duration, given the data collection and analytic methods used?

- Are seasonal and monthly variability accounted for when evaluating and determining the significance of impacts to duration? Are these appropriate timescales or is finer-scale (e.g. day-level) analysis needed?

- What is the management reference point – that is, the baseline standard for comparison – for ecological risk in this river/estuary system?

3) Prepare a review of the current state of science and evaluate

- whether new conceptual and analytical tools would be used if an estuarine study for setting instream flows were conducted in the present,

    - including their advantages and disadvantages for use in assessing precise water levels within estuary channels with changing river discharge and tide.

- This will include but is not limited to

    - gathering and summarizing research that has updated the scientific understanding of areas relevant to the estuary study since the Duke Engineering Study was completed,

    - summarizing methods used to set instream flows in tidally influenced areas in other locations,

    - identification of methods that could be used today to determine instream flow levels in estuarine tidally influenced areas.

- This review will also assess whether knowledge about estuarine health and function have changed significantly and in what way in the past 20 years, including
    - how changes in the watershed could impact the influx of water, sediment, nutrients, and so on, and
    - especially relative to juvenile salmonid rearing habitat, density-dependent rearing habitat limitations, and the role of over-channel tidal/freshwater inundation in estuary food webs.

4) Present its findings to the Task Force and answer questions from the Task Force to further clarify and discuss its findings including, if applicable, a description of data gaps for potential future areas of study.

Task Goal Statement:

Provide a peer review of the estuary study portion of the Duke Engineering Report and review the current state of information/methods for determining instream flows related to estuaries to inform the Task Force.

Task Expected Outcomes:

List of committee experts and their disciplines, final report(s) reviewing the Duke Engineering Report estuary study and the current state of information/methods for determining instream flows related to estuaries, and a facilitated discussion with the Task Force of key findings from the report(s).

APPENDIX B: COMMITTEE ROSTER

For questions related to the peer review process, contact:
Yasmeen Hussain, Program Officer – yasmeen.hussain@washacad.org

Michael Goodchild (Chair) – good@geog.ucsb.edu

Dr. Michael Goodchild is an Emeritus Professor of Geography at the University of California, Santa Barbara. Until his retirement, Dr. Goodchild was Jack and Laura Dangermond Professor of Geography, and Director of UCSB's Center for Spatial Studies. His research interests center on geographic information science, spatial analysis, and uncertainty in geographic data. Dr. Goodchild was elected member of the National Academy of Sciences and Foreign Member of the Royal Society of Canada, member of the American Academy of Arts and Sciences, and Foreign Member of the Royal Society and Corresponding Fellow of the British Academy. He was Chair of the National Research Council's Mapping Science Committee, and of the Advisory Committee on Social, Behavioral, and Economic Sciences of the National Science Foundation. Dr. Goodchild has a PhD in geography from McMaster University, and has received five honorary doctorates.

Rebecca Flitcroft – rebecca.flitcroft@usda.gov

Dr. Rebecca Flitcroft is a Research Fish Biologist and Team Leader in Landscape and Ecosystem Management at the US Forest Service. Her research on watershed analysis and management is focused on statistical and physical representations of stream networks in analysis and monitoring that more realistically represent stream complexity and connectivity for aquatic species along four primary lines of research: multiscale salmonid ecology; stream network analysis; climate change and salmonid life history; and integrated watershed management. Dr. Flitcroft conducts studies to expand the existing knowledge base about the interaction between complex life-history phenology of Pacific salmonids and their environment, particularly in the context of climate change as it relates to available habitats in coastal draining systems. Dr. Flitcroft is involved with local, regional, and state-wide efforts in Oregon to develop coordinated management techniques focused on watersheds. Dr. Flitcroft holds a PhD in Fisheries Science from Oregon State University.

Eric Grossman – egrossman@usgs.gov

Dr. Eric Grossman is a Research Geologist at the Pacific Coastal and Marine Science Center of the United States Geological Survey and a Research Associate at Western Washington University. His expertise includes coastal geology and marine geophysics, coastal ecosystems and restoration, estuaries, hydrodynamics, local and indigenous knowledge, and fluvial and littoral sediment transport. Dr. Grossman is a founding member of the Skagit Climate Science Consortium. He has received the USGS Western States Diversity Award, Washington State Governor's Smart Communities Award, Coastal America Award, USGS Western Region Science

Strategy Success Award, and Department of Interior Partners in Cooperation Award. Dr. Grossman has a PhD in marine geology and geophysics from the University of Hawaii.

Se-Yeun Lee – lees@seattleu.edu

Dr. Se-Yeun Lee is an Instructor in Civil and Environmental Engineering at Seattle University, and was previously a Research Scientist with the Climate Impacts Group at the University of Washington. Dr. Lee has been involved in interdisciplinary research focusing on understanding and modeling the complex interactions between climate, hydrology and natural resource management, and particularly climate change impacts on hydrology in the Skagit Basin. She has authored peer-reviewed research papers, book chapters, and reports, and has worked with and advised managers and decision-makers. Dr. Lee has a PhD in civil and environmental engineering from the University of Washington.

John Rybczyk – rybczyj2@wwu.edu

Dr. John Rybczyk is a Professor of Environmental Sciences at Western Washington University. He is an applied wetlands ecologist and uses an integrated field and modeling approach to study the effects of climate change, and rising sea-levels specifically, on coastal systems to predict the resiliency of estuarine systems. Dr. Rybczyk's focus has been on the delta systems of the Pacific Northwest, including the Skagit River delta system. He is a founding member of the Skagit Climate Science Consortium. Dr. Rybczyk has a PhD in Oceanography from Louisiana State University.

Mark Wigmosta – mark.wigmosta@pnnl.gov

Dr. Mark Wigmosta is a Chief Scientist and Technical Lead for the Computational Watershed Hydrology Team at the Pacific Northwest National Laboratory. Mark is also a Distinguished Faculty Fellow in the University of Washington Department of Civil & Environmental Engineering. He has over 30 years of experience in distributed watershed hydrology, including the potential impacts of land-use and climate change on water resources and renewable energy. Dr. Wigmosta was the principal developer of the Distributed Hydrology-Soil-Vegetation Model (DHSVM), which has been widely used in forest management applications. Mark has authored more than 55 peer-reviewed research papers and book chapters, and his research on renewable energy received an American Geophysical Union Editor's Choice Award. Dr. Wigmosta has a PhD in environmental engineering and science from the University of Washington.