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Proposed Scope for a Comprehensive Hydrologic Study of the Skagit Estuary

Prepared for the Joint Legislative Task Force on Water Supply

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TABLE OF CONTENTS

BACKGROUND

The estuary of the Skagit River is a complex system bounded on one side by Skagit Bay of the Salish Sea, and at its upstream end by the branching of the Skagit River immediately downstream of the city of Mount Vernon. It is fed by water that accumulates in the upper Skagit Valley, which extends into the Cascade Mountains and the Canadian Province of British Columbia and contains several impoundments. Water that reaches the estuary is especially critical during the low-flow season of late summer, and is also subject to flooding and inundation during the high-flow winter season. The flow of the river is critical to the life cycles of salmonid species, to agriculture in the fertile Skagit Valley, for recreation and domestic use, and for its esthetic value. All of these uses and concerns must compete, especially during the period of water scarcity in late summer. Thus, decisions about these competing concerns need to be based on the best possible scientific understanding of the processes at work in the estuary.

In 1999, Washington State commissioned Duke Engineering to conduct a study of the estuary with a view to understanding its hydrology and ecology ("the Duke Study")[1] as a scientific basis for management decisions about such topics as in-stream flow levels and water withdrawals. However, a 2021 peer review of that study by a committee of the Washington State Academy of Sciences ("the WSAS Review") [2] found many weaknesses in the data that were collected and the methods of analysis that were used, and identified ways in which a new study might take advantage of developments since the 1990s: new data sources, better sampling designs, cheaper sensors, better understanding of fish ecology, and new simulation models. Also in 2021, a parallel analysis was conducted by the State of Washington Water Resources Center that examined supply and demand factors in the entire Skagit Basin ("the WRC Supply and Demand Study").[3]

Following receipt of the WSAS Review, a meeting of the Joint Legislative Task Force for Water Supply in the Skagit ("the JLTF") was held on 4 October 2021 to discuss possible next steps. The following motion was moved by Senator Wagoner and approved:

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[1] Duke Engineering. 1999 Duke Estuary Study, section 3 of the "Final Technical Report: Lower Skagit River Instream Flow Studies."

[2] WSAS (Washington State Academy of Sciences) 2021. Independent Peer Review of the Estuary 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. January 2021.

[3] Jonathan Yoder, Siddharth Chaudhary, Brittany Duarte, Correigh Greene, Jordan Jobe, Gabe LaHue, Cindy Maroney, Guillaume Mauger, Harriet Morgan, Julie Padowski, Kirti Rajagopalan, Crystal Raymond, Matthew Rogers, Nathan Rossman, Navdeep Singh, Britta Timpane-Padgham, Chad Wiseman, Jason Won. 2021. Skagit Water Supply and Demand Synthesis. Story Map Series Prepared for the State of Washington Joint Legislative Task Force on Water Supply. https://doi.org/10.7273/4n11-9k73

> *I [Senator Wagoner] move that WRC and WSAS scope a single proposal on prioritizing and addressing knowledge gaps that were raised by the Skagit Water Supply and Demand Synthesis and the Duke Study peer review. In the scoping process, WRC and WSAS shall utilize an iterative process including interactions with the committee to assist in clearly articulating goals and assisting in the development of the scope.*

The JLTF formed a Working Group of stakeholders ("the Working Group"), who were invited to develop outline proposals that might form part of that scope. A total of nine such "Outline Proposals" were submitted, three of which directly addressed the issues of the estuary. These were subsequently discussed by the WSAS committee (now the WSAS Science Committee on the Skagit River, in short "the Committee"), and iterated with the stakeholders. What follows here is the result of that iterative process, in the form of a proposed scope for a Comprehensive Hydrologic Study of the Skagit Estuary (CHSSE).

INTRODUCTION

What follows in this proposed scope is founded on the following principles. First, like the WSAS as a whole, the Committee "provides expert scientific and engineering assessments to inform public policy making" (WSAS Mission at https://washacad.org/aboutus). We recognize that many interests and perspectives inform policy decisions; our focus is entirely on the best available science to inform those decisions. Second, what follows is designed to show the full range of research that will be needed to fill gaps in the current scientific understanding of the estuary, as identified in the WSAS Review and the WRC Supply and Demand Study. Third, we recognize that conditions in the estuary vary markedly through the annual cycle, and from year to year, and that full understanding can only result from an extended, multi-year period of observation and modeling. Thus, we have attempted to identify and describe those research investments that are needed immediately, and those that will allow for and support research over multiple years.

Finally, we suggest that the potential impacts of changing climate on the Skagit watershed provide an overarching issue that will need to be considered as research is conducted. Those impacts range from the timing and amount of the snowpack at the headwaters, to sea-level rise in Skagit Bay, changing salinization in the estuary, and changes in summer water temperature in the river. The uncertainties (what we know and with what level of certainty, what we don't know, and what we need to know) that are inherent in all research will be amplified in a future where change is occurring more rapidly than before. Acknowledging upfront that our current understanding will also change over time as new information becomes available, it is essential that what we know now continues to be informed by what we learn over time.

The next six sections describe key framing elements of the proposed scope of research to understand more fully the Skagit estuary as a whole, rather than as a set of unconnected parts. While we recognize that current funding for research is limited and that not all of this research can be funded now, these framing elements represent a synthesis of ideas that surfaced in the Duke Review, the WRC Supply and

Demand Study, the three Outline Proposals dealing with the estuary, comments received from members of the Working Group, and the discussions of the Committee. The elements are followed by the Committee's outline of proposed research investments that, if worked on over several years, will create a more complete hydrologic picture of the estuary necessary to provide insights needed to guide its management.

I. PROPOSED FRAMING ELEMENTS OF THE CHSSE

The Committee recommends that six elements should together frame the CHSSE. These six elements all recognize weaknesses that were identified in the Duke Review and will need to be addressed if the CHSSE is to be successful in filling scientific knowledge gaps today and in the coming years. Following the identification of these elements, specific proposals are presented for near-term and longer-term research.

1. Topographical and seasonal inundation dynamics

The focus of the CHSSE should be on the Skagit tidal delta, that is, the portion of the lower river that is historically subject to tidal variation in elevation and salinity. At its most extensive, this area might be seen as including: 1) the lower river below the USGS gage in Mt. Vernon, 2) wetlands and channels along and between the North and South Forks of the delta (from the Swinomish channel to wetlands north of Stanwood), 3) wetlands and channels along the Swinomish Channel, and 4) wetlands and mudflats in Skagit Bay and Padilla Bay between mean higher high water and mean lower low water. Forcing factors at extents greater than these areas (e.g., tides, upriver flows) could factor into the topographical and seasonal inundation dynamics element, but these dynamics will not be directly analyzed from the perspective of the combined effects of tidal processes and river flow on fish and their habitat in this framing element.

2. Temporal variation in aquatic habitat characteristics

A variety of fish species use the Skagit delta at different time periods based on their life histories. Flow conditions and water use needs also have seasonal patterns. The temporal variation within the delta requires that research projects evaluate flow conditions suitable for habitat forming processes and fish habitat use over an entire water year. Recognizing that annual variability exists in flow conditions, multiple water years that represent an adequate range in natural conditions should be evaluated. This element addresses the critical need to establish a baseline condition that captures the range of variability be established as a basis for comparison for management and climate change scenarios.

3. Synthesis of habitat suitability index development of targeted fish species

A synthesis of existing fish knowledge would identify the needs of fish that can be incorporated into the data acquisition program and into subsequent analysis and modeling. Substantial advances have been made in species-specific knowledge of fish life history diversity with respect to the use of lower-river/estuary ecotone and estuary habitats in the past two decades. While the Duke report focused on juvenile Chinook salmon, other species/life stages use the estuary. These include nonlisted salmon species with juvenile life stages that use deltas (coho and chum), listed species whose juvenile life stages migrate through the delta (steelhead & bull trout), and adult stages of some of these species that migrate through the delta during low flow periods (e.g., Chinook). This element would encompass efforts to provide a broader, updated synthesis of this knowledge.

4. Hydrodynamic Modeling

Several efforts have been made in the past two decades to model the hydrology of the estuary using software tools such as the Skagit Hydrodynamic Modeling project, or SHDM. Models will need to be updated to accommodate changes in the geometry of the estuary channels and recent advances in our understanding of the interactions between hydrology and fish. The three-dimensional finite elements used in models should be adequate to address the critical periods of low flow and inundation, and the influence of tides. While a comprehensive review of all past modeling efforts may not be possible or necessary due to time and resource constraints, a compendium of them would be useful to inform ongoing research.

5. Integration of the estuary and the upstream basin

While it may be appropriate to consider the estuary in isolation when addressing several key issues, nevertheless there are scientifically important ways in which the tides and upriver flows influence and are influenced by the estuary. Water temperature in the estuary, a key issue for fish habitat during late-summer low flow, is influenced by tides and by upstream factors such as shade, groundwater seepage into streams, and glacier melt. Some fish species need upstream habitat to complete their life cycle. Over time, the CHSSE will need to address these issues, and to find ways to fill gaps in our knowledge. For example, the DHSVM-RBM model may be valuable in modeling unregulated downstream flow and water temperature, and it may be possible to revisit the Duke study and its analysis of upstream fish habitat in the light of new developments in species-specific habitat needs for diverse life history expression. If necessary, these unregulated flows and temperatures can be used as input to a model of the reservoir system to examine regulated flows. This element encompasses work to address how these two systems, the estuary and the upstream basin, impact each other.

6. Measurement error, uncertainty, and error propagation

Every element of the CHSSE will be subject to uncertainty, from the measurement of the geometry of the estuary’s channels through to the estimates and predictions from the various models and analyses. It is important that best efforts be made to estimate these uncertainties, and to propagate them through to each study’s conclusions using techniques such as simulation. This element is meant to ensure that these uncertainties are recognized and addressed appropriately in each specific research proposal.

Water Supply Scenarios Due to Climate Change to be Examined when better data are available from the research projects described above

Many aspects of the estuary environment are already changing and are expected to continue to change in the coming decades due to changes in hydrology, glaciers, water temperature and/or sea level rise due to projected warmer climate, changing management practices, and sedimentation and channel erosion.

These and other causes of change, including low probability but high impact catastrophic events such as tsunamis and earthquakes, will influence the estuary and its habitat availability across the estuary. They should be enumerated and examined as different water supply scenarios in the CHSSE.

For illustrative purposes, some key scenarios could include

- A number of climate emissions scenarios
- Downscaling of global climate models to regional analyses
- Projections for changes out to several future dates, e.g., 2040 and 2080
- Simulations of a variety of water years
- Simulations of various land use scenarios

In particular, the hydrodynamic modeling system described below would provide a valuable tool to better understand the extent and timing of climate-induced changes and the impact on water supply as well as in-channel and estuary habitat. Given the uncertainly in climate predictions, the use of an ensemble-based approach is suggested.

II. OUTLINE OF PROPOSED RESEARCH INVESTMENTS

This section describes proposed research investments aligned with the six framing elements outlined above. With the available funding, not all projects can be funded or completed in FY 2023 (by June 2023). The Committee recommends a focus on the following near-term investments with current funding. This focus will add to and update the current understanding of the estuary while simultaneously paving the way for longer-term and multi-year research projects within the estuary, consideration of findings from upriver research, and ongoing (or forthcoming) insights about changes in the Skagit watershed that will likely occur due to a changing climate.

The total cost estimate of the set of near-term projects to be conducted in FY 2023 (Projects 1 – 5 below) is $510,000, with the caveat that specific project costs are best determined by the research teams that will conduct the work. Approximations of cost are included in Table 1. Three additional projects are recommended as longer-term projects that build on the findings of the near-term work.

Table 1: List of proposed near- and long-term research projects of the CHSSE

FY 2023		
Project 1	Data collection about topographical and seasonal inundation dynamics	$75,000
Project 2	Improve understanding temporal variation in aquatic habitat characteristics	$50,000
Project 3	Conduct a synthesis of habitat suitability index development of targeted fish species	$100,000
Project 4	Conduct Hydrodynamic modeling	$210,000
Project 5	Develop life cycle models that integrate the estuary and the upstream basin	$75,000
Total		**$510,000**
FY 2024 and Beyond		
Project 6	Long-term data collection to understand temporal variation in aquatic habitat characteristics	TBD
Project 7	Expand and continue hydrodynamic modeling	TBD
Project 8	Continue integration of the estuary and the upstream basin	TBD

Near Term Projects – FY 2023

Project 1: Data collection about topographical and seasonal inundation dynamics

The committee considers it important to initiate data collection as early as possible, rather than waiting until hydrodynamic modeling begins. A first step will be to compile existing data that has been collected by various programs since the era of the Duke Study (1999), such as the Skagit HDM[4]. These data could be reviewed, updated, and incorporated as updates to existing reports and analyses where appropriate, with gaps identified where new date need to be collected.

In particular, because of the high cost and other limitations of sensors and measuring devices at the time, the Duke Study was able to build only a limited observational picture of the estuary. The CHSSE will be able to take advantage of the very rapid development of new technologies over the past two decades to build a much more complete picture. Specifically, the following could be investigated and if feasible employed:

- airborne and satellite-borne LiDAR to map elevations at fine resolution across the estuary (since LiDAR does not penetrate water, data might be collected at the lowest possible tide levels to best capture tidal channel and tidal flat topography);
- ground-based sensors that can be used to acquire point observations of water depth, flow rates, water temperature, and salinity; and
- fine-resolution multispectral imagery acquired from satellites, aircraft, and drones.

This work can be conducted by a team of academic and/or private consultants with the charge of 1) compiling and organizing existing topographical and seasonal inundation data, 2) updating existing reports and analyses with more recent data; and 3) gathering new data, e.g., LiDAR and ground-based sensor data, and fine-resolution multi-spectral imagery. The proposed product would be an up-to-date compendium of estuary specific physical data that would contribute to future modeling efforts.

Project 2. Improve understanding temporal variation in aquatic habitat characteristics

As noted above, the temporal variation within the delta requires that research projects evaluate flow conditions suitable for habitat forming processes and fish habitat use over an entire water year. Recognizing that annual variability exists in flow conditions, multiple water years that represent an adequate range in natural conditions should be evaluated.

The committee recommends a research project to define a baseline condition that captures the range of variability of flows be established as a basis for comparison for management and climate change scenarios over time.

A physics-based hydrodynamic model could be validated for a range of flows to ensure that the model accurately characterizes the complex relationships between river/fluvial processes and tidal processes. Some of this work has already been completed by PNNL as part of the refinement of the Skagit HDM[5], but among the issues to be examined in more detail is whether the model would simulate channel/bed-

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[4] Skagit HDM, September 2017. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26867.pdf

[5] Ibid.

forming processes (such as erosion and sediment transport) or assume the bed is fixed in time, which while computationally easier to accomplish, may not be as useful for understanding variation.

In addition, water surface elevation data should be acquired at multiple locations within the study area in the estuary to ensure a high degree of validation. Once the physical model is validated, it can be used to evaluate a range of water years with known tidal and river flow information from existing data and weather stations. The model can be used for an analysis of scenarios at a variety of temporal scales ranging over the full water year, to the full chinook smolt outmigration period, and to shorter time periods of extreme high or low flow events. The model could also be used to evaluate a variety of scenarios including management and climate change scenarios.

This work can be conducted by a team of researchers familiar with the data and methodologies of the current models (e.g., the Skagit HDM). The proposed product would be an up-to-date understanding of flow conditions over several years that identify areas suitable for habitat forming processes and fish habitat use over an entire water year.

Project 3. Conduct a synthesis of habitat suitability index development of targeted fish species.

An extensive review of fish knowledge in the Skagit should be conducted and include available published literature and other ongoing (and therefore incomplete) research efforts within the basin to avoid duplication. These studies will likely have different conditions compared to published studies in other systems. It also will be useful to summarize and leverage other data from the estuary, to understand how the variety of fish utilize the estuary (including their presence and density related to seasonal stream flows), and to develop a method to establish habitat suitability indices (HSIs) of targeted fish species.

Each of the projects are described briefly below could provide critical information in the near term:

3A. Utilize the Skagit River System Cooperative's (SRSC) fish monitoring dataset (1995-present) to examine responses of multiple fish species to flow and associated habitat conditions.

SRSC has focused on juvenile chinook salmon, and a current goal of SRSC is to use these data to develop models addressing fish-habitat relationships in the delta.

3B. Conduct a multivariate analysis of water metrics to determine the attributes tied tovarious flow conditions.

River flow is often considered a master variable for determining habitat conditions in rivers, with extreme flows as one parameter affecting fish measured in Skagit streams. In addition to stream flow, water quality measurements such as temperature and invertebrates are measured in lowland tributaries. This project would conduct a multivariate data analysis of habitat attributes (e.g., velocity, temperature, invertebrates, and estuary/lower main channel salinity) integrating landscape drivers (e.g., land use, shade, water availability). Data would be collected from fish habitat, with evaluation of multiple dimensions of habitat characteristics and potential impacts (andtheir spatial variation). Integrating these metrics could help determine best management practices, such as flow management versus other management interventions (e.g., improved shade).

3C. Develop species, life-stage specific, and seasonal HSIs for fish species occupying the estuary.

Using available methodologies[6], developing estuary specific HSIs would improve understanding of how changes in water level, flow, and substrate affect species and life stage specific habitat use. Skagit River specific HSIs for the estuary could be calculated to establish a baseline condition of the habitat needs of fish. These HSIs could then be calculated for the study area under a variety of management and climate scenarios to determine if there are any significant positive or negative changes.

3D. Conduct a hydrodynamic evaluation of the influence of freshwater flows upon estuarine habitat forming processes and habitat use by salmon, addressing current and future climate scenarios for the Skagit delta and associated Skagit Bay nearshore.

River flow can affect many habitat features in estuaries, the extent of wetland marshes, and migratory connectivity for salmon populations. Many research-based improvements such as hydrodynamic models of tidal inundation and river flow, incorporation of climate impacts, use of lidar and other remotely sensed information, and improved understanding of the fish habitat use have been developed for the Skagit Basin, but have not yet been used to update conclusions about contributions of river flow to tidal delta habitats used by fish.

This project would construct an integrated model of fish habitat opportunity in the delta and nearshore as functions of existing and potential future delta footprint, tidal inundation, temperature, and most importantly, the Skagit River hydrograph. It also would integrate existing datasets and model products, such as:

- The Salish Sea Model (Khangaonkar et al. 2018, 2021) and Skagit Delta Hydrodynamic Model (Yang and Khangaonkar 2006, 2009), which examine circulation, tidal inundation, river flow, and other water properties in the delta and nearshore.
- Analyses linking salinity variation, vegetation change, and sediment accretion,
- Modeled climate impacts including downscaled air temperature and Skagit river flow (see Skagit Story Map), and tidal delta impacts of sea level rise and changes in circulation (Northwest Science, 2016, Volume 90 (1)).
- lidar-based maps of tidal elevation and channel structure (Beechie et al. 2018)
- 20+ years of fish monitoring data (Greene et al. 2021) coupled with physical observations, enabling evaluation of site-specific fish-habitat relationships.

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[6] https://www.google.com/books/edition/Development_and_Evaluation_of_Habitat_Su/88pBfPKB-cAC?hl=en&gbpv=0

Over time, this project will help improve the understanding of:

- Fish habitat: The integrated model will evaluate what levels of seasonal flow optimize residency of salmonids across the tidal delta and nearshore for the full rearing season, taking into account changes to the delta wetland footprint.
- Future climate: Climate impacts impose both seasonal constraints (e.g., increased temperatures) as well as potential opportunities (increased inundation from sea level rise) for fishes in the tidal delta, so incorporating scenarios of these cumulative effects isnecessary to address the influence of seasonal flow.
- Surface water: The new study will better quantify how much water is needed to support fish habitat in the delta and nearshore, in turn providing new and improved information on the potential for water use by people.

Project 4. Conduct hydrodynamic modeling

Data to be used in modeling should be acquired from the estuary over an extended period of time—at least five years—in order to gain knowledge of annual variations, especially during the critical periods of late-summer low flow and winter inundation. If the period of active research in the CHSSE is limited by practical issues such as budget resources, plans should be made in the near term to identify available data and then to identify key data needed to collect to fill gaps, as well as to sustain the acquisition of critical data beyond this period of active research. To accomplish that goal, we recommend the following projects.

4A. Create a working group of researchers to identify models and data domains.

A short-term planning effort could be organized to bring together researchers to identify data that can be gathered now, as well as their sources and limitations, that ultimately can be used in future modeling, as suggested in Table 1. Similarly, a working group could also identify which models to prioritize, exclude or add in order to address questions of interest, as suggested in Tables 2 and 3, and thus bring to light the strengths and limitations of various models.

Table 2: Examples of data inputs for hydrodynamic model

Data element	**Existing data**	**Data source**	**Limitations**
Wetland surface elevations	Lidar (years)	USGS NOAA lidar consortium	Higher uncertainty in wetted channels, highly vegetated areas
Delta water surface elevations	Water level gages (2010-2020)	Skagit River System Cooperative	Spatial coverage limited to fish sampling sites in NF, SF, bayfront.

Delta temperatures and salinities	Water level gages (2010-2020)	Skagit River System Cooperative	Spatial coverage limited to fish sampling sites in NF, SF, bayfront.
Other	TBD	TBD	TBD

Table 3: Preliminary examples of models to be examined to address questions of interest

Model domain	**Key SOW requirements**	**Key outputs**	**Possible model**	**Key model assumptions**
Delta hydrodynamics	Model entire delta subject to inundation	Water surface elevations Area inundated Velocity Water depth Duration of inundation Duration of specific water depth ranges Shear stress Temperature	Salish Sea Model/Skagit River HDM	Model solutions are exact (no error)
Freshwater flows	Physics-based flow inputs below Mt. Vernon gage	Spatiotemporal snowpack, snowmelt, streamflow, and water temperature	Skagit DHSVM-RBM	Model extent currently stops at Mt. Vernon Models natural flows (i.e. no reservoir operation)
Freshwater flows after reservoir operations	Reservoir operations	Regulated streamflow at key locations (i.e dam operation is included)	SkagitSim Reservoir Operations Model	
Other	TBD	TBD	TBD	TBD

4B. Perform additional modeling to simulate future water temperatures to determine the flow levels needed to maintain water temperatures at levels that are consistent with salmon recovery goals.

A key factor affecting fish – in particular the flow levels needed to maintain healthy habitat conditions for salmon – is water temperatures. Warmer air in the future could lead to in hospitable water temperatures even if instream flow targets are met.

For surface water, water temperature will likely be a dominant constraint on low flows, given the implications for salmon viability. For groundwater, baseflow rates, and the proportion of streamflow composed of baseflow from groundwater, could play a significant role in moderating temperatures. More data and modeling could also provide information related to water quality for municipal and agricultural uses.

Future water temperatures can be estimated with the River Basin Model (RBM), which was designed to work with DHSVM flows and provides physically-based water temperature estimates. The model can also be used to simulate the relationship between flow levels and water temperatures at specific times in the future. Modeling results could be confirmed, in part with eDNA monitoring for upstream fish presence.

Project 5. Develop life cycle models that integrate the estuary and the upstream basin

This project would develop life cycle models that incorporate spatial variation to account for movements of fish within the watershed. Because fish are capable of moving and migrating, understanding the quantitative impacts of flow management to fish populations requires a spatially informed model.

Many fishes are highly mobile and move both upstream and downstream to find high quality habitat (e.g., food, refuge, optimal temperatures, or dissolved oxygen). This is especially true for Pacific salmon, which must eventually migrate to the ocean at some point in their life cycle. Movements within a watershed complicate assessment of the effects of flow-related impacts to habitats in portions of the watershed upon the entire population because patchy high-quality habitats may "buffer" impacts of poor-quality habitats, even as they reduce the total amount of habitat in the basin. In addition, evaluating flow-related impacts should account for multiple limiting factors or cumulative impacts to habitat at different life stages.

Because they incorporate multiple life stages, all life cycle models address multiple possible limiting factors. Many life cycle models have been developed to account for spatial variation and some can accommodate for movements of individuals within basins, and these can readily be adapted for the Skagit River basin.

Long Term Projects -- FY 2024 and beyond

All of the following research projects would also contribute to a deeper understanding of the Skagit estuary, and build on the work completed in the first set of projects described above. They would be conducted beyond the next fiscal year, so no cost estimates are included at this time.

Project 6. Long-term data collection to understand temporal variation in aquatic habitat characteristics

A commitment to data collection over an extended period of time—at least five years—will be needed in order to gain knowledge of annual variations in other parameters such as sediment, salinity and temperature. The complex relationship between these parameters and flow is less understood in the estuary and would be much more difficult to model on a shorter time scale.

As first priority, the CHSSE should be closely aligned with Duke 1999's and IFIM methods in the use of water surface elevation and duration of inundation as a first step toward understanding the relationship between flow/tide and habitat as defined through habitat suitability indices (HSIs). If there is a finding that water withdrawal or climate scenarios could significantly affect water surface elevations, the WSAS could re-engage in scoping of future work to better understand how the changes in flow due to the evaluated scenarios may or may not affect sediment processes, temperature, salinity, or invertebrates.

In addition, other issues to research over the next several years include:

Sediment processes: Evidence suggests that sediment processes are somewhat episodic. Sediment transport also has thresholds for initiation of movement and transport related to flow rate/depth and sediment characteristics. Sediment transport processes (suspended load and scour/bedload) tend to occur at higher freshwater flows rates, rather than the lower flow rates (below 10,000 cfs) where the greatest stresses may currently exist, but more research is needed.

Water temperature: Water temperature may be impacted by a variety of water supply scenarios. A conservation of mass analysis could be conducted to refine the importance of water withdrawals on temperature.. It is important to be able to differentiate potential changes in water temperature due to natural conditions, water withdrawals scenarios, and other issues like shade in riparian zones. Under existing conditions most of the estuary does not have shade, including extensive mudflats, marshes and tidal channels.

Project 7. Expand and continue hydrodynamic modeling

Glaciers in the upper Skagit basin contribute substantial water to streamflow in late summer, the time of lowest flows and greatest likelihood of scarcity. These glaciers are sensitive to climate change and changes in glacier melt water will affect surface water availability in the basin in the future.

The DHSVM hydrologic model used to simulate streamflow includes aglacier model that simulates melting glaciers and the contributions of glacier melt water to streamflow. However, the glacier model has not been thoroughly validated to ensure it adequately represents glaciers, glacier melt water, and the response of glaciers to warming. Additional model refinement could improve on the glacier simulations, thereby ensuring thatfuture streamflow estimates accurately reflect changes in glacier contributions to flows. This refinement would hopefully help to reduce the bias in the streamflow, particularly for summerlow flow times when water scarcity is of greatest concern, and would improve also flow simulations for the tributaries. In addition, model refinement would enable better understanding of effects of glaciers on summer flows and will improve understanding of low flow and summer temperature constraints on cold-water fishes.

Project 8. Continue integration of the estuary and the upstream basin

Conduct a habitat and flow assessment that includes habitat beyond the lower reaches of the Skagit River basin that could provide more current understanding of the system and food web.

The Skagit River is a dynamic hydrologic system, and habitat has likely changed at the sites examined in the Duke report in 1999. While it may be appropriate to consider the estuary in isolation when addressing several key issues, nevertheless there are scientifically important ways in which the tides and upriver flows influence and are influenced by the estuary. Over time, the CHSSE will need to address these issues, and to find ways to fill gaps in our knowledge and improve our understanding of flow-based constraints on fish populations.

For example, water temperature in the estuary, a key issue for fish habitat during late-summer low flow, is influenced by tides and by upstream factors such as shade, groundwater seepage into streams, and glacier melt. Some fish species need upstream habitat to complete their life cycle.

In addition, the DHSVM-RBM model may be valuable in modeling unregulated downstream flow and water temperature, and it may be possible to revisit the Duke study and its analysis of upstream fish habitat in the light of new developments in species-specific habitat needs for diverse life history expression. If necessary, data about these unregulated flows and temperatures can be used as inputs to a model of the reservoir system to examine regulated flows.

An update of understanding of the watershed would provide current data, as recent analyses assume depths and velocity profiles have remained similar. Conditions likely vary across the watershed, so a better understanding of how flow conditions influence spawning and rearing habitat will depend upon better studies of fish, their habitats, and patterns of flow that incorporate spatial variation. Such a study could be done by applying the IFIM modeling approach used by Duke Engineering (1999) to other reaches with different cross-sectional areas and associated substrate types with updated HSIs for updated portions of the watershed. This modeling should be done for both reference reaches (little impacts to the hydrograph, riparian conditions, and aquatic substrates) as well as places associated with various impacts to flow, temperature, and riparian conditions.

This study could fill a critical gap in knowledge about surface water if it expands the IFIM analysis to tributaries that are critical for fish habitat, rather than only the mainstem. With information about flow levels that are optimum for fish habitat, the DHSVM surface flow modeling and projections could be used to understand the frequency with which these flows are met now and how that would change with climate change. While current DHSVM modeling includes all the tributaries, it is difficult to use this information when it is not known what the optimum flows are for fish in the same locations.

Finally, and as noted above, we recognize that many interests and perspectives inform policy decisions. Our focus in preparing this scope for a Comprehensive Hydrologic Study of the Skagit Estuary has been on research that can provide the best available science to inform future decisions. We consider the projects described here as representing the range of research that will be needed to fill gaps in the current scientific understanding of the estuary, as identified in the WSAS Review and the WRC Supply and Demand Study. We recognize that conditions in the estuary vary markedly through the annual cycle, and from year to year, and that full understanding can only result from an extended, multi-year period of observation and modeling. Thus, we have attempted to identify and describe those research investments that are needed immediately, and those that will allow for and support research over multiple years.

APPENDIX A: COMMITTEE ROSTER

For questions related to this project, contact:
Donna Gerardi Riordan, Executive Director – donna.riordan@washacad.org

WSAS Committee on the Skagit Water Supply

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.

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.