# Effects of Projected Twenty-First Century Sea Level Rise, Storm Surge, and River Flooding On Water Levels in the Skagit River Floodplain and Estuary

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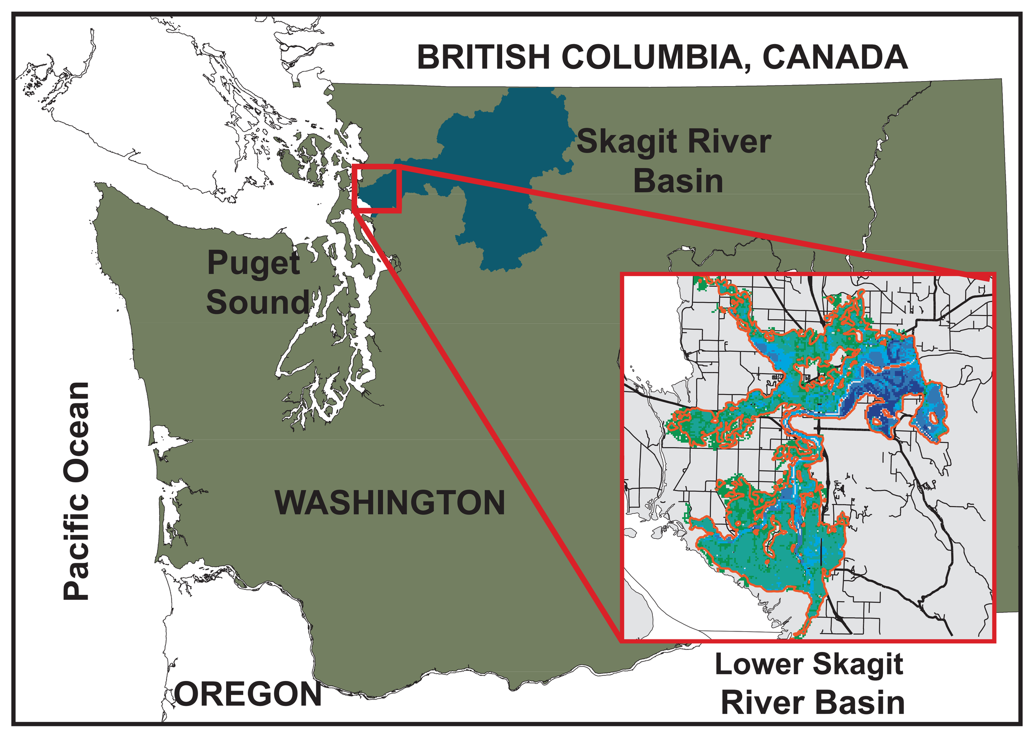
## INTRODUCTION

Near coastal environments have been identified as some of the most likely to be impacted by climate change. Observed changes in Puget Sound sea level and flood magnitudes are in line with those projected by previous climate change impacts studies. Current understanding of the combined effects of these changes is relatively low and has promoted us to explore the ways in which these two influence near coastal ecosystems and infrastructure. Specifically, this project examines the effects of climate change on areal flood inundation by exploring the combined effects of sea level rise and riverine flooding. The project utilizes a chain of numerical models to quantify the climate change altered hydraulic conditions in the Skagit River floodplain.

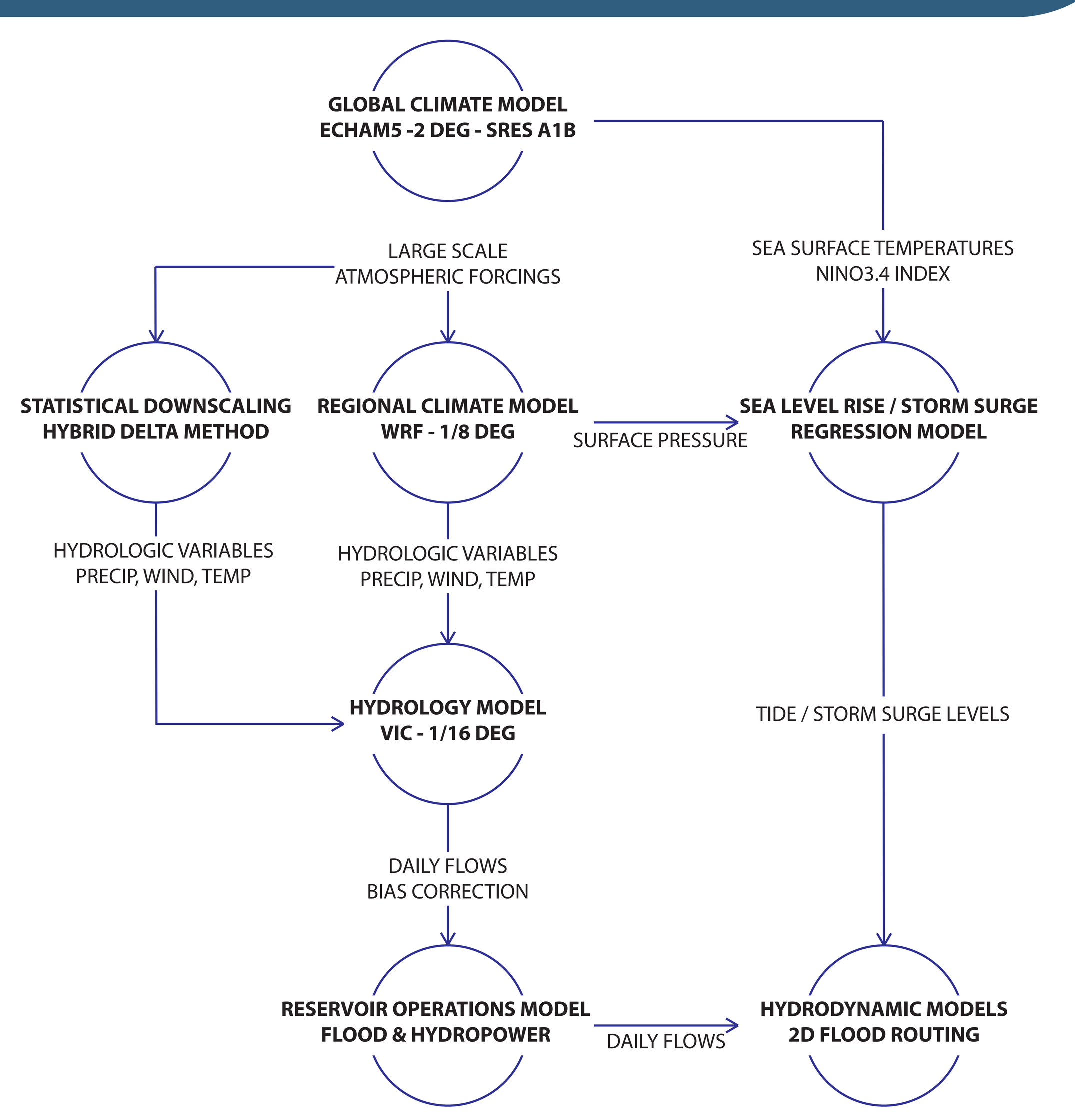
## PROJECT GOALS

1. Incorporate Regional Climate Model (RCM) projections into ongoing climate impacts studies.
2. Use RCM projections to develop temporally consistent storm responses (coincident floods and storm surges).
3. Use projected river flows and storm surges to evaluate physical flood impacts using hydrodynamic models.

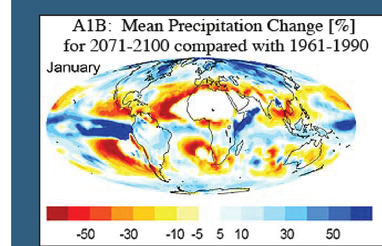



## PROJECT OUTLINE

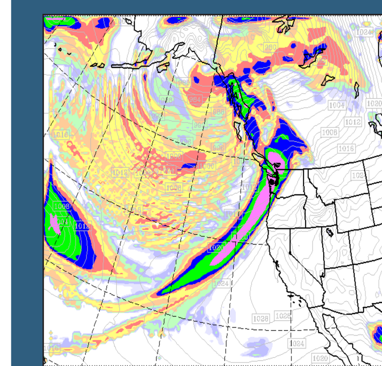
This project relies heavily on work previously completed by others, especially in regards to the complex climate and hydrologic modeling. The figure below outlines the process of developing local scale flood projections beginning with global climate model results.



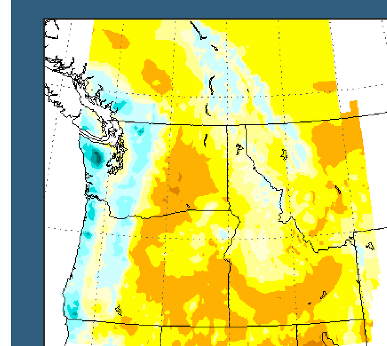

## DATA & MODELS




**GLOBAL CLIMATE MODEL**: The ECHAM5 climate model, SRES A1B, was used by Salathe et al. (2010) as the large scale forcing for the regional climate model. Monthly gridded equatorial sea surface temperatures (SSTs) were extracted from this large-scale data set to include ENSO effects.

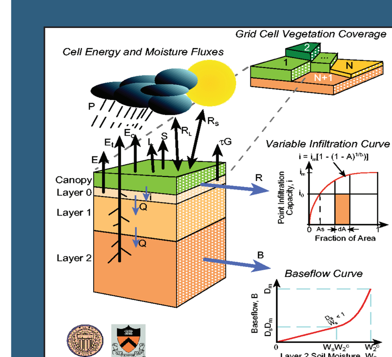


**REGIONAL CLIMATE MODEL**: The Weather Research Forecast (WRF) model was used to dynamically downscale GCM projections. Because WRF is run at higher spatial (1/8th degree) and temporal (6 minutes) resolutions than the large scale GCM, it provides much more realistic weather events than are otherwise possible. Additionally, dynamic downscaling allows weather patterns to change according to first principle relationships.
The RCM outputs were also bias corrected to match historical statistics. Citation: Salathe et al. (2010).

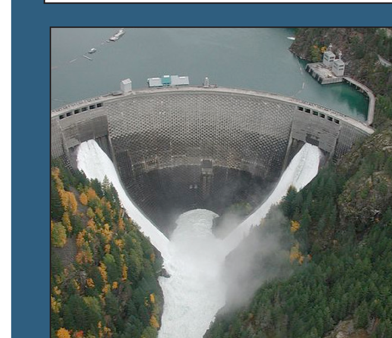


**STATISTICAL DOWNSCALING**: Hybrid-delta method was used to statistically downscale raw GCM data. This process projects the monthly changes indicated by the GCM onto a historical data set. A complete description of the methods used in developing the statistically downscaled climate data can be found in Hamlet et al. (2010).

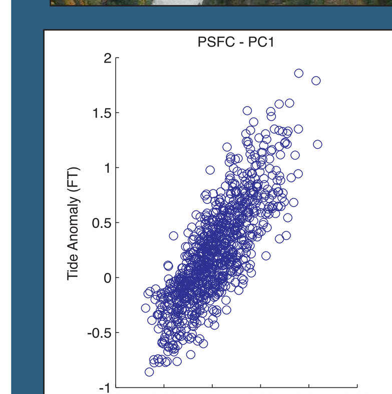
## METHODS

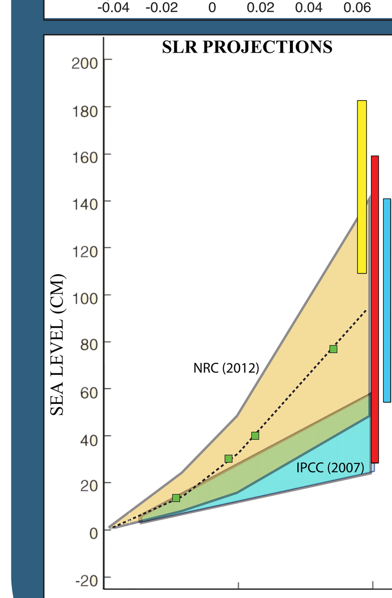


**HYDROLOGY MODEL**: The Variable Infiltration Capacity (VIC) model was run at 1/16th degree resolution. All input variables (Tmin, Tmax, Wind, and Precip) were obtained from the bias corrected RCM outputs or the statistically downscaled GCM outputs. Routed VIC outputs were also bias corrected using a quantile mapping approach with USGS daily flows.



**RESERVOIR MODELS**: The reservoir model used in this study was constructed following the methodology outlined in Lee et al. (2011). In short, the model simulates reservoir operation at a daily timestep while meeting prescribed hydropower demands, minimum flow requirements and flood control targets.




**SEA LEVEL RISE & STORM SURGE**:
- The principle harmonic constituents were fit to the measured hourly water levels using a least-squares approach.
- These constants were then used to provide a time series of predicted hourly tides.
- The differences from the predicted and measured tides were summarized at a daily timestep.
- A regression approach was used for each month to estimate future water levels given a set of atmospheric variables from the GCM.
- An iterative process was used to determine which variables best described tidal anomalies experienced in the Puget Sound. Local pressure, the 1st (regional covariance) and 3rd (SW-NE dipole) EOF signals, and ENSO were the only variables found to be significantly impactful on the anomaly.
- TideAnomaly = f (Pressure, Pressure3DayAverage, PC1, PC3, ENSO)
- Regression during winter months yields $R^2 > 0.8$.
- Sea level rise was uniformly added to the $Tide_{anom}$ for each time period based on projections outlined by NRC (2012).

## MODEL RUNS

| Time Period | Hydrologic Source | Storm Surge Source | Sea Level Rise (ft) | Description |
|---|---|---|---|---|
| | Gridded Observations | Reanalysis | 0 | Gridded observations 1916-1999 while WRF data spanned 1970-1999. |
| **1970-1999** | H.D. - 2040s - ECHAM5 | Reanalysis | 1.35 | Hybrid Delta 2040s using WRF reanalysis as time consistent storm surge forcings. |
| **1970-1999** | H.D. - 2080s - ECHAM5 | Reanalysis | 3.02 | Hybrid Delta 2080s using WRF reanalysis as time consistent storm surge forcings. |
| **1970-1999** | WRF | WRF | 0 | WRF - ECHAM5 20th century climate run. |
| **2010-2039** | WRF | WRF | 0.41 | WRF - ECHAM5 SRES A1B, 2010 – 2039. |
| **2040-2069** | WRF | WRF | 1.42 | WRF - ECHAM5 SRES A1B, 2041 – 2069. |

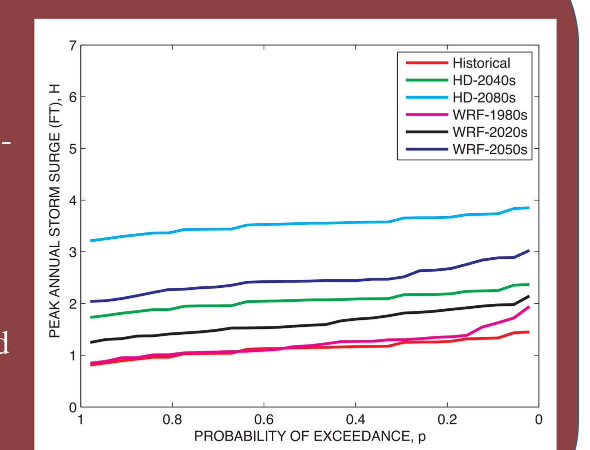
## HYDRODYNAMIC MODEL RUNS & RESULTS

- The hydrodynamic model used to evaluate flood inundations in the Skagit River basin was developed by FEMA and USACE.
- No further development, calibration was performed as a part of this study.
- Rather, the flood events produced by the modeling efforts of this study were fed to the hydrodynamic model (Flo2D) as shown in this table.

| Climate | Storm | Peak Daily Flow (cfs) | SLR (ft) | Inundation (acres) |
|---|---|---|---|---|
| **Observed** | FEMA | 203,835 | 0 | 42,266 |
| **HD-2040s** | 1.14*FEMA | 232,372 | 1.35 | 66,248 |
| **HD-2080s** | 1.32*FEMA | 269,062 | 3.02 | 73,583 |
| **WRF-2050s** | Storm 1 | 192,151 | 1.42 | 51,365 |
| **WRF-2050s** | Storm 2 | 158,614 | 1.42 | 30,972 |
| **WRF-2050s** | Storm 3 | 150,560 | 1.42 | 22,259 |
| **Sensitivity** | 2040s SLR Only | 203,835 | 1.35 | 56,951 |
| **Sensitivity** | 2040s Flood Only | 232,372 | 0 | 73,605 |

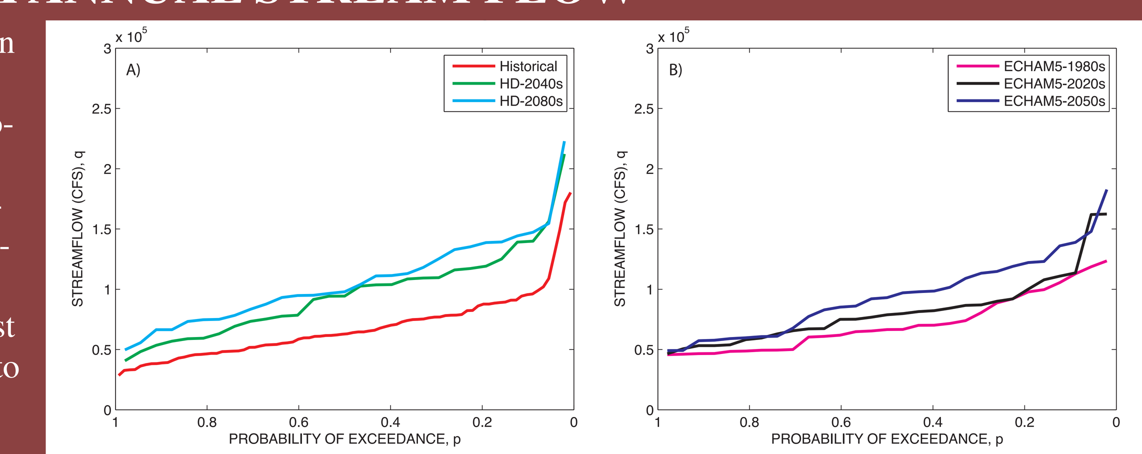
## PEAK ANNUAL STORM SURGE

- Good match between ECHAM5 1980s and Historical 1980s time periods.
- Minimal change in actual storm surge.
- Change in peak annual storm surge is dominated by sea level rise.




## PEAK ANNUAL STREAM FLOW

- Both downscaling approaches show increases in flood magnitude.
- Statistical downscaled runs (A) exhibit more robust increases in flood magnitude.
- Dynamically downscaled runs (B) are less conclusive due to smaller sample size and more degrees of freedom.
- Both downscaling approaches show most robust increases in the more common flood events (2 to 10 year return interval)




## HYDRODYNAMIC MODELING

### Scaled Q-100 Floods:

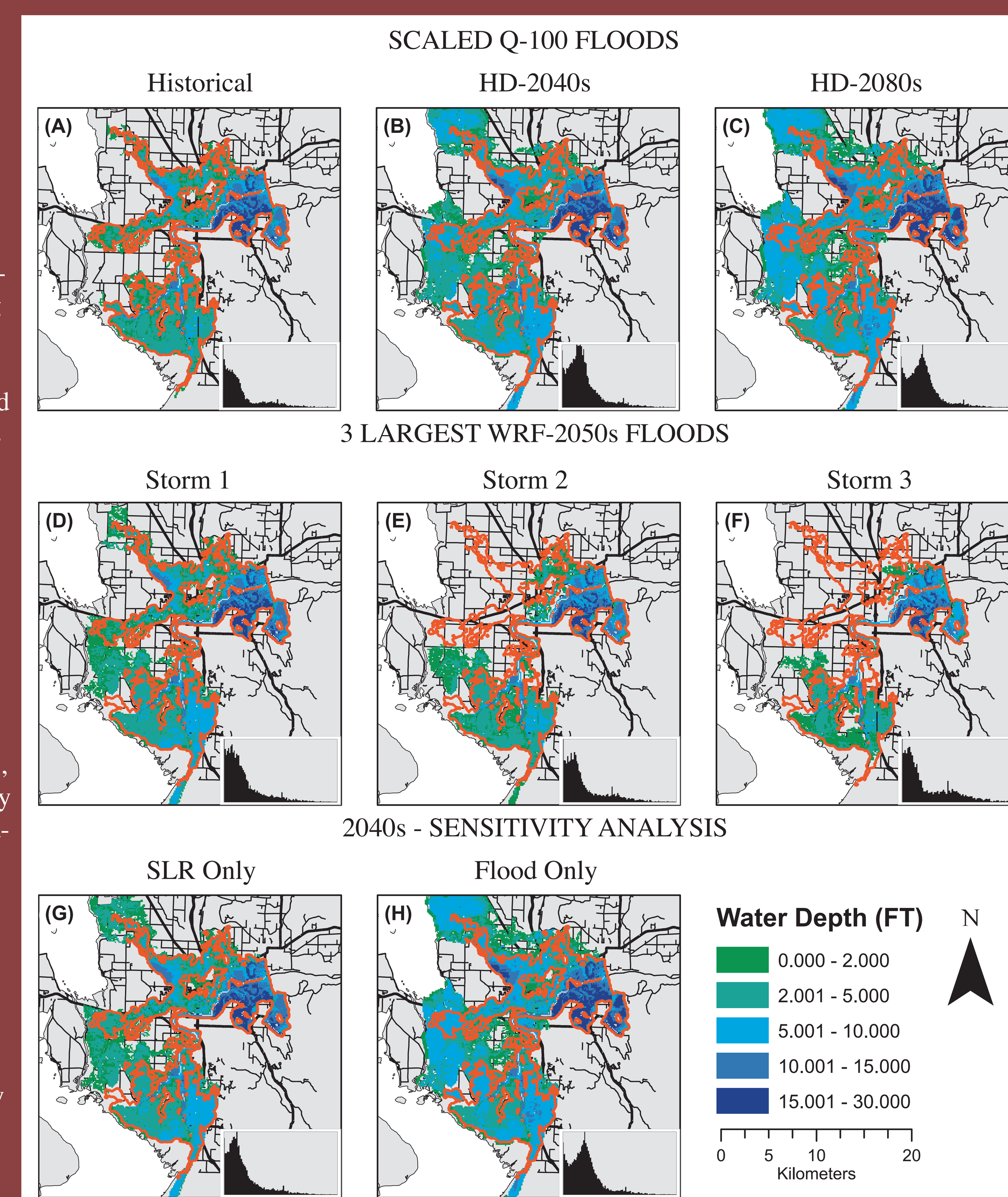
- The "100-yr" flood (p=0.01) was determined by fitting extreme value distributions to the peak annual flow.
- The 100-yr flood for the 2040s and 2080s was found to be 114% and 132% of the historical 100-yr flood.
- For the scaled Q-100 flood runs, the historical 100-yr flood was scaled up using these factors.
- Using the scaled up floods combined with their respective SLR, the 2040s and 2080s show increased flood inundations of 57% and 74% respectively.

### 3 Largest WRF-2050s Floods

- The 3 largest flood events from the WRF-2050s were input into the hydrodynamic model. Temporally consistent tides, storm surge, and sea level rise were used as the downstream boundary condition.
- Although flood volume of "Storm 1" was less than the historical 100-yr flood, the changes in the downstream boundary produced flood inundation of 125% relative to the historical 100-yr flood.

### 2040s - Sensitivity Analysis

- A sensitivity analysis of hydrodynamic model was run by varying only the upstream or downstream boundary condition.
- We found that for flood magnitudes equal to those of the 2040s, the majority of the lower basin floods, regardless of the height of SLR.
- SLR alone, also produces larger flood inundations, especially in the coastal areas of the basin.




Results from the hydrodynamic model for the no levee failure scenarios. The red outlines represent the bounds of the historical Q100 event and are provided for spatial reference. The histograms demonstrate the increase in average depth for the larger floods in the basin.

## Conclusions

- Using regional climate model results, we demonstrate a process for developing and implementing temporally consistent climate change projections of flood magnitudes and sea level.
- Using a range of flood and sea level scenarios and methods, we produce future flood maps for the Skagit River basin.
- Skagit River flood magnitudes are predicted to increase up to 32% by the 2080s.
- The increase in flood magnitudes and sea level combine to yield increased areal inundation of up to 74%.
- Using a scenario-based approach is one way of handling the uncertainty involved in multi-model event prediction.

## REFERENCES

1. Committee on Sea Level Rise in California, Oregon, and Washington. (2012). Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. National Research Council. Washington, D.C.: The National Academies Press.
2. Hamlet, A.F., P. Carrasco, J. Deems, M.M. Elsner, T. Kamstra, C. Lee, S-Y Lee, G. Mauger, E. P. Salathe, I. Tohver, L. Whitely Binder, 2010, Final Project Report for the Columbia Basin Climate Change Scenarios Project, http://www.hydro.washington.edu/2860/report/.
3. Lee, Se-Yeun, A.F. Hamlet, 2011: Skagit River Basin Climate Science Report, a summary report prepared for Skagit County and the Envision Skagit Project by the Department of Civil and Environmental Engineering and The Climate Impacts Group at the University of Washington.
4. Salathé, E.P., Leung, L.R., Qian, Y., and Zhang, Y., 2010. Regional climate model projections for the State of Washington. Climatic Change, doi:10.1007/s10584-010-9849-y.

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