# PLANNING FOR CLIMATE CHANGE AND FLOODING IN THE LOWER SKAGIT RIVER BASIN

Joe Hamman

October 3, 2012

Floodplain Management and Planning for River Communities
URBDP 598C

CLIMATE IMPACTS GROUP

Department of Civil and Environmental Engineering

# GLOBAL CLIMATE CHANGE

# GLOBAL CLIMATE CHANGE

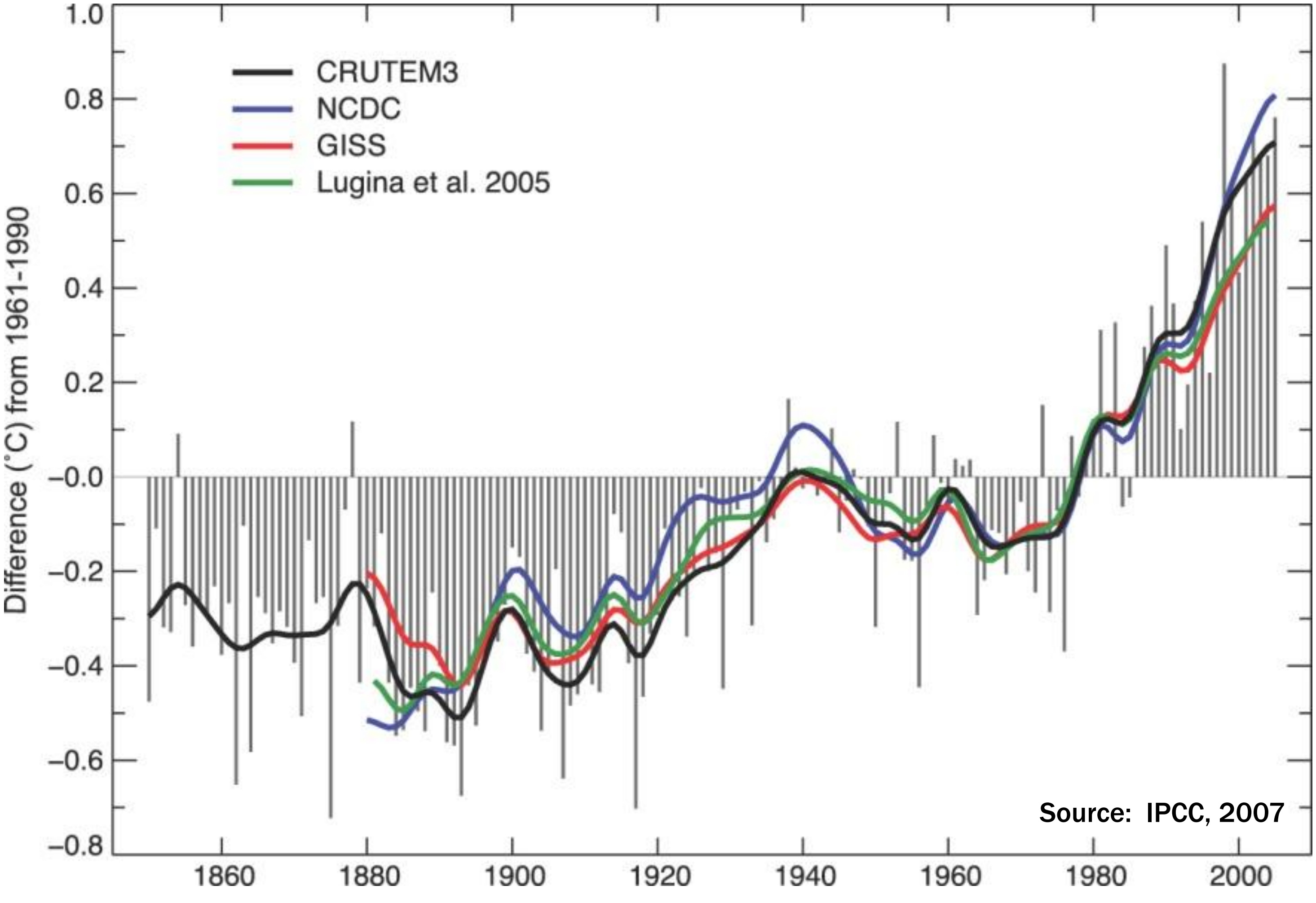
# PRESENTATION OUTLINE

1. Introduction to climate change and climate science
2. Implications of climate change for river flooding and sea level rise
3. Overview of the Skagit River Watershed and flood history
4. Climate change impacts on flooding in the Skagit River
5. Questions and Discussion

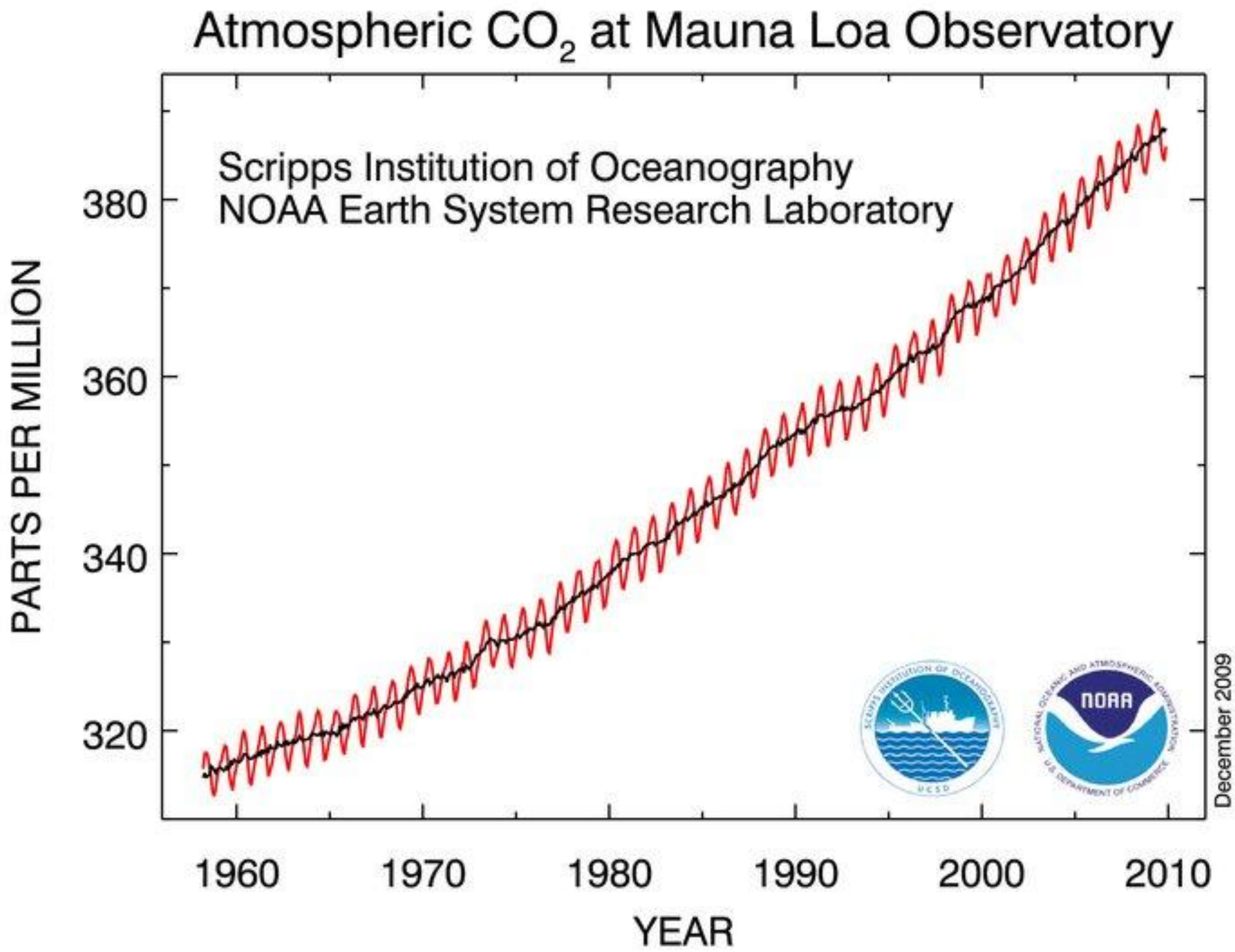
**Aerial computer generated depiction of large flood event from Burlington to Mount Vernon to Padilla Bay**
Picture Courtesy Skagit County Public Works Department

# GLOBAL CLIMATE CHANGE
# THE BASICS

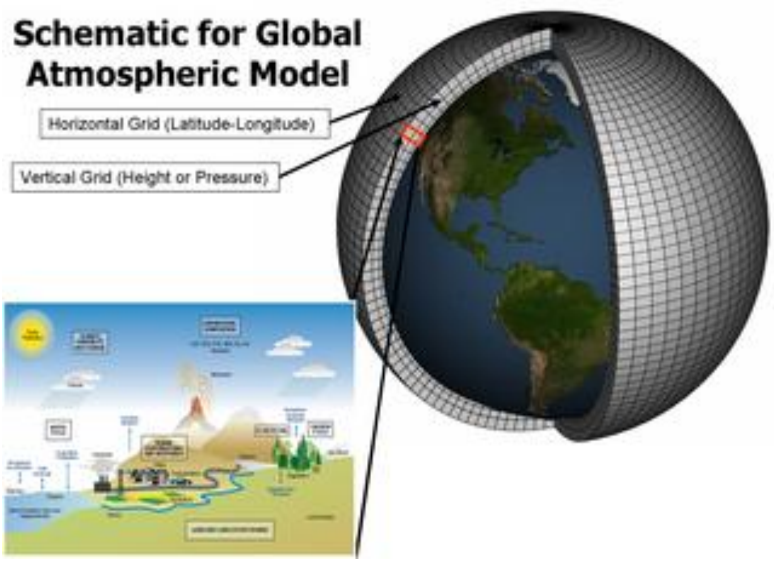
20th century warming between 0.75 and 1°C



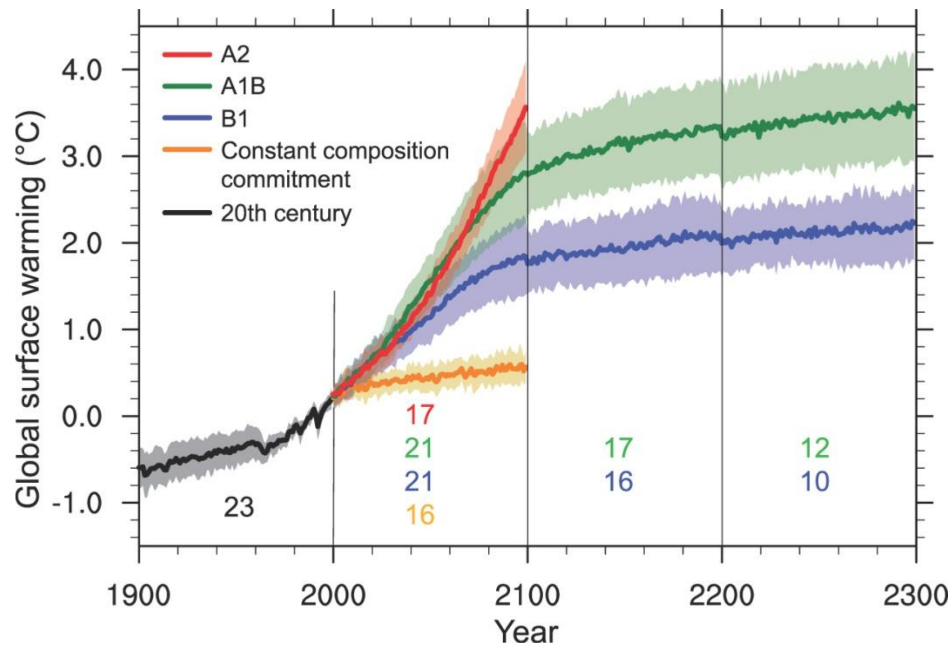
# OBSERVED TRENDS IN $CO_2$



# GLOBAL CLIMATE MODELS



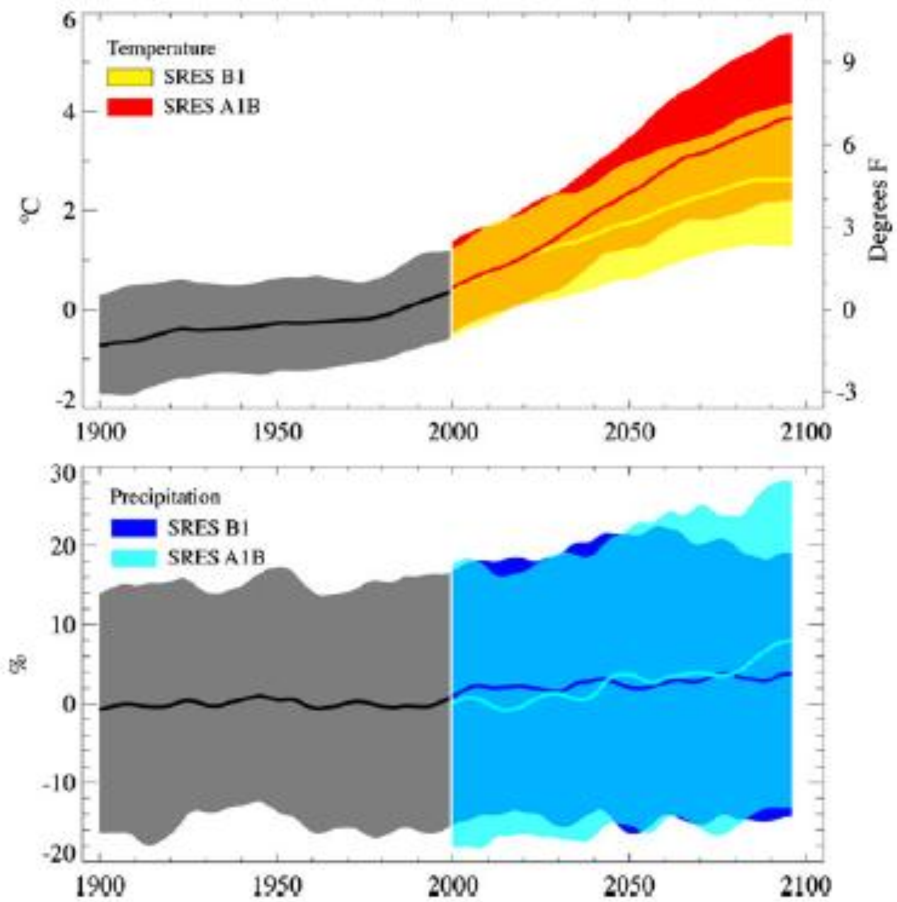

**Projections from GCMs**
**21st century warming**
**between 1.5 and 3°C**




**Source: IPCC, 2007**

# FUTURE CLIMATE CHANGE IN THE PACIFIC NORTHWEST

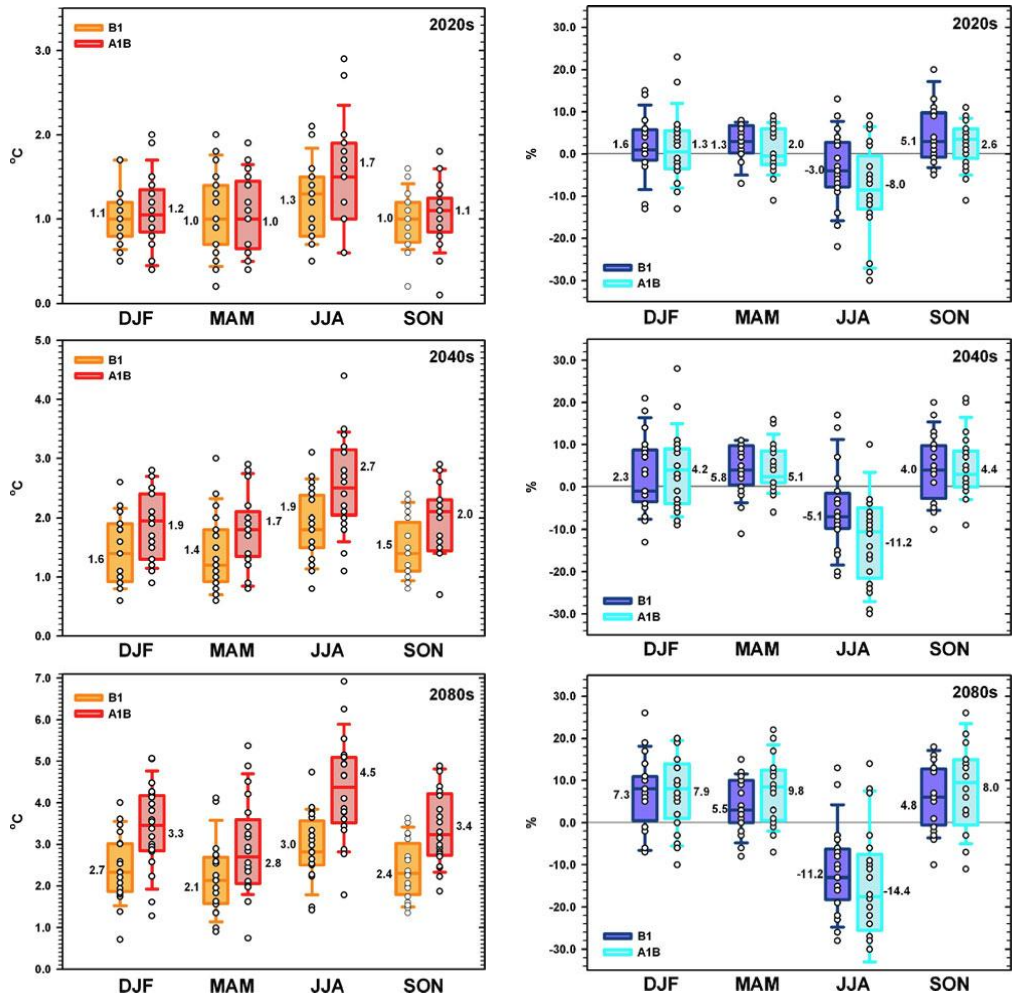
- Mote et al. (2010) looked at the output from 20GCMs
- Strong signal-to-noise ratio for changes in temperature
- No clear signal for changes In precipitation
- Temperature
  - 2020s – 1.1°C
  - 2040s – 1.8°C
  - 2080s – 3.0°C
- Precipitation
  - +1% to +2%




Source: Mote et al, 2010

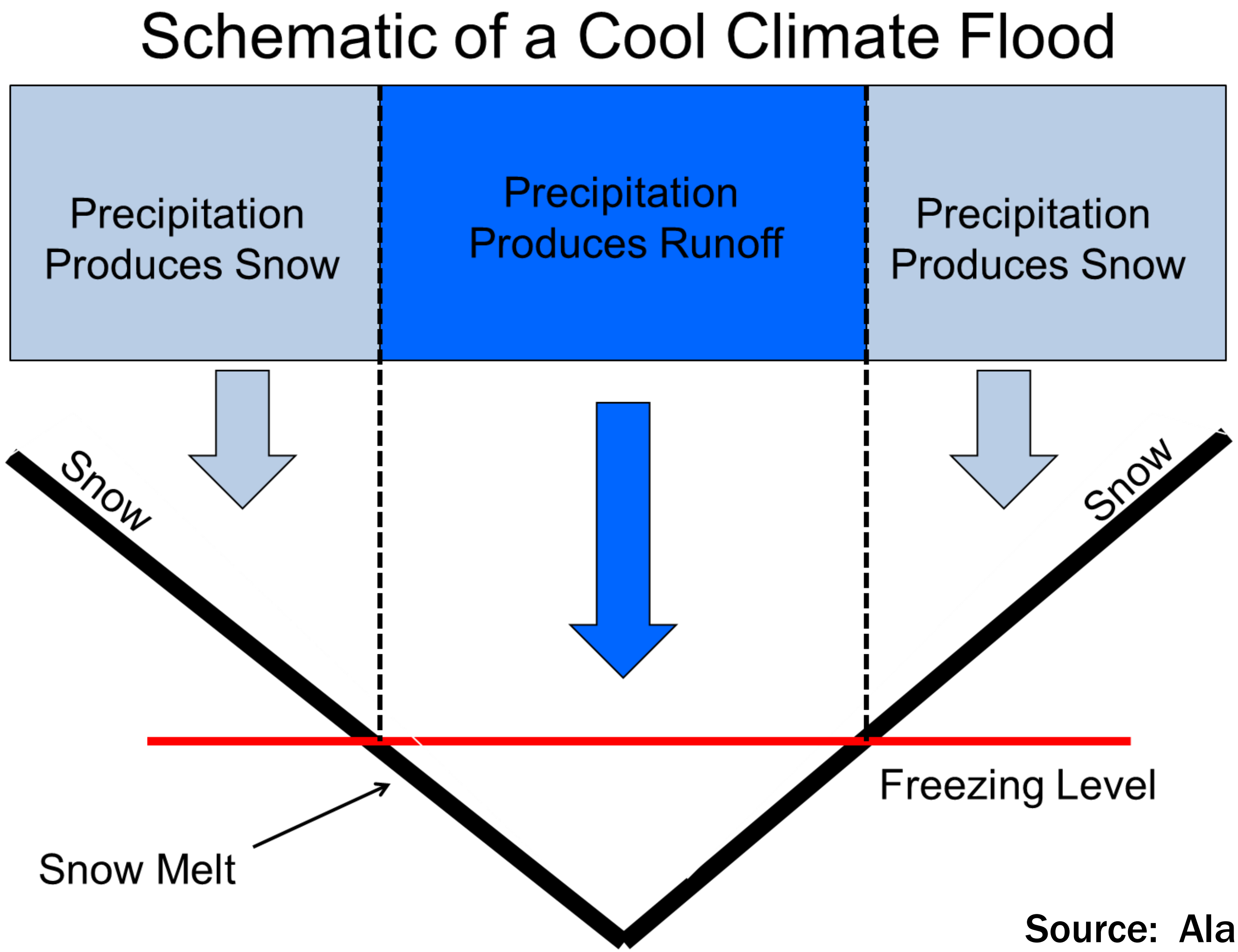
# FUTURE CLIMATE CHANGE IN THE PACIFIC NORTHWEST

- Seasonal Temperature
  - Largest increases during Summer months
- Seasonal Precipitation
  - Increase in Winter/Spring/Fall precipitation
  - Decrease in Summer precipitation




Source: Mote et al, 2010

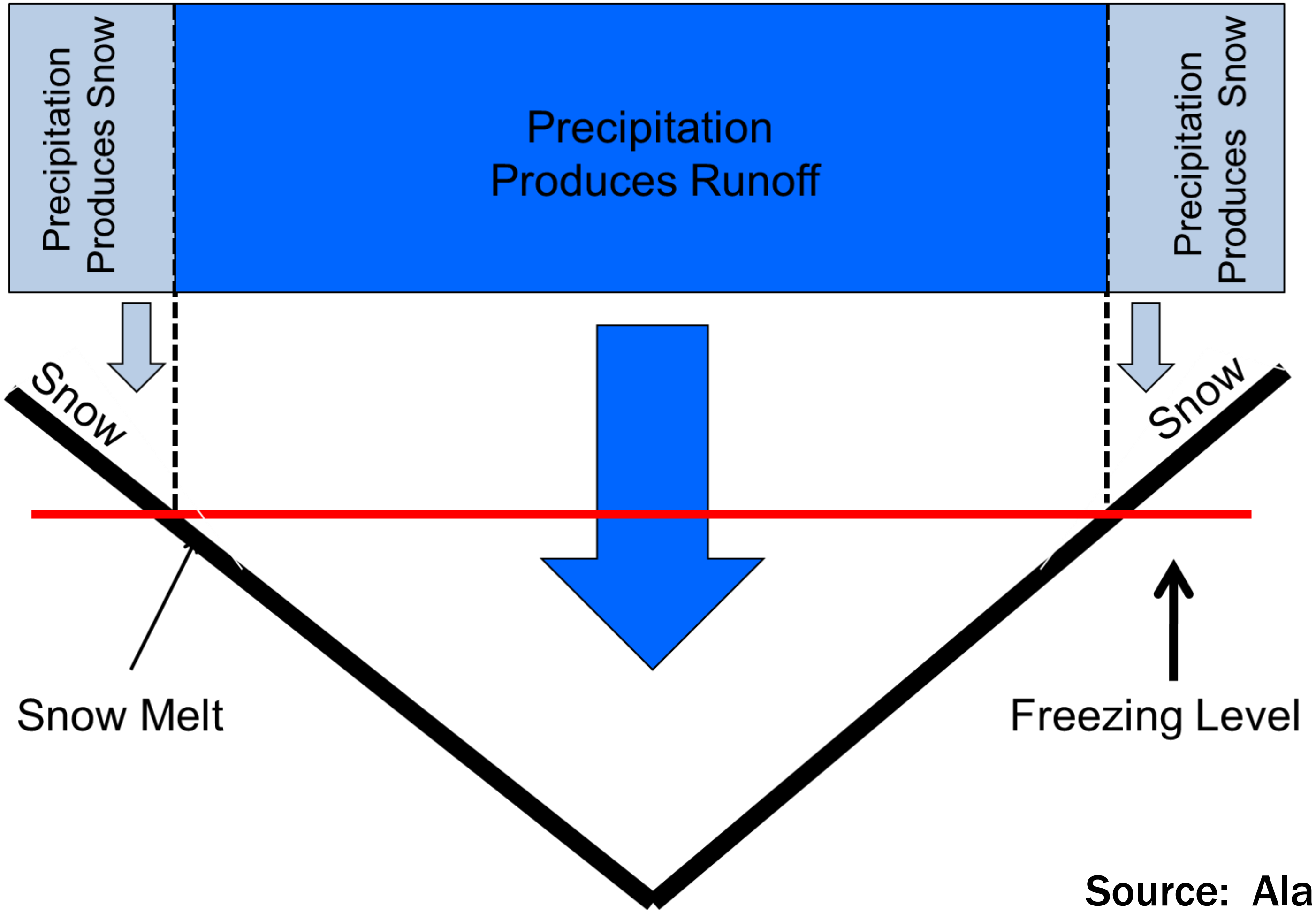
# IMPLICATIONS OF WARMING ON HYDROLOGY




Source: Alan Hamlet

# IMPLICATIONS OF WARMING ON HYDROLOGY

Schematic of a Warm Climate Flood




**Source: Alan Hamlet**

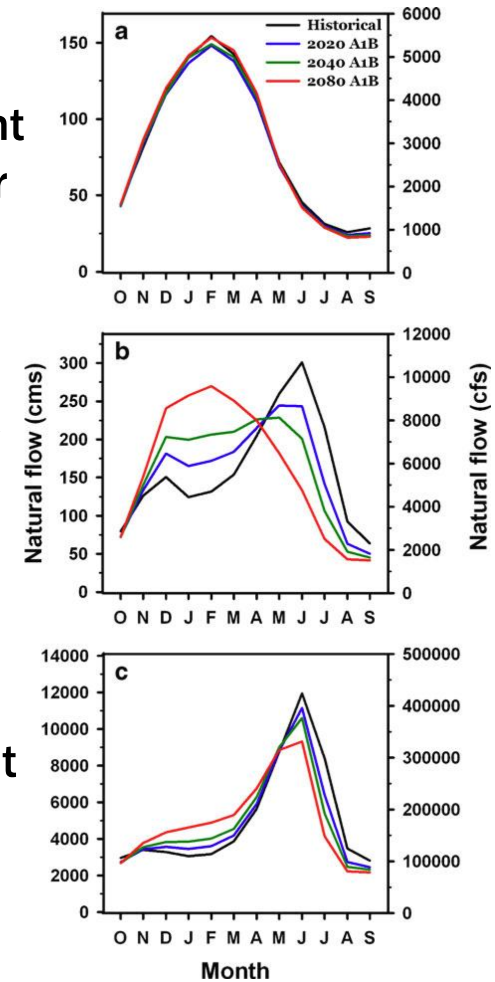
# CHANGES IN STREAMFLOW TIMING

- Changes due to warmer temperatures and increased Winter precipitation
  - Rain Dominant Basins: small increases
  - Transient Rain-Snow Basins: shift from spring peak to Fall/Winter peak
  - Snowmelt Dominant Basins: decrease in Spring/Summer flow

Rain Dominant
Chehalis River

Transient Rain-Snow
Yakima River

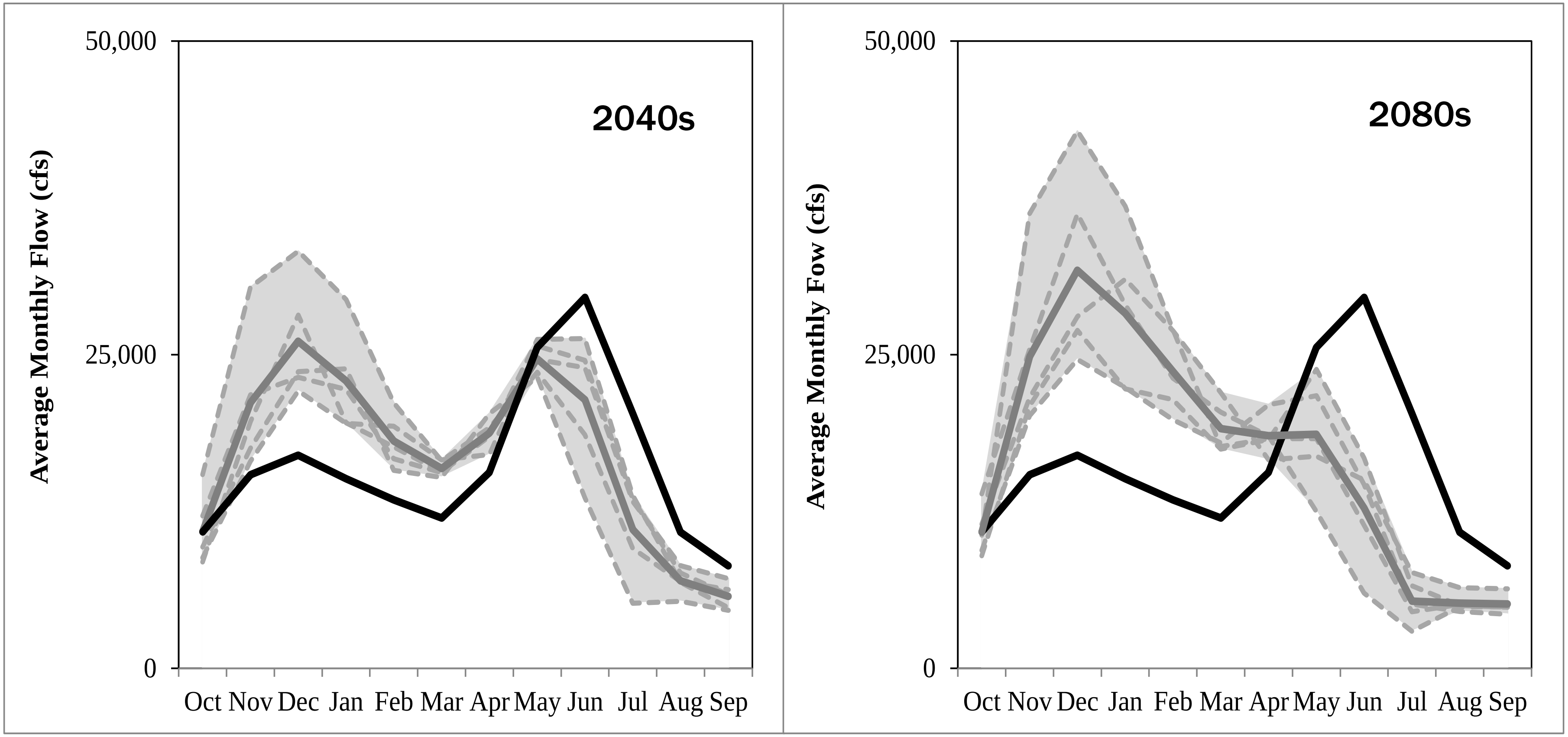
Snowmelt Dominant
Columbia River




Source: Elsner et at., 2010

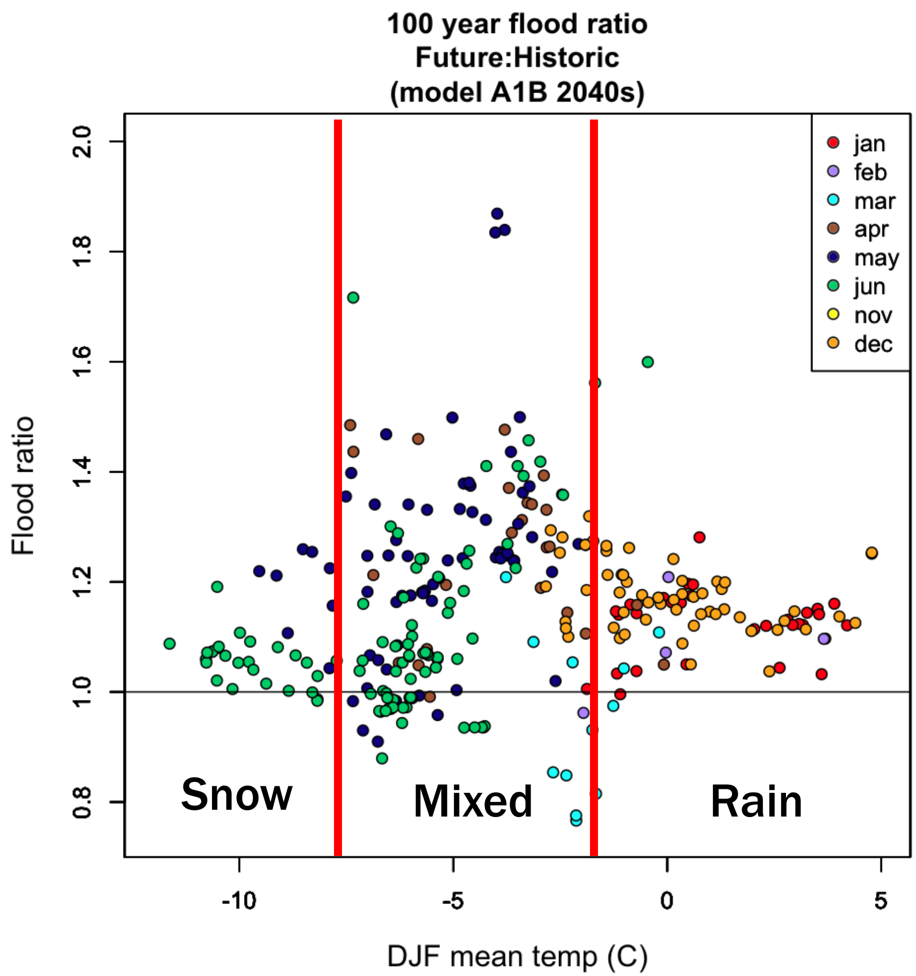
# CHANGES IN MONTHLY AVERAGE STREAMFLOW

## Skagit River Basin near Mount Vernon



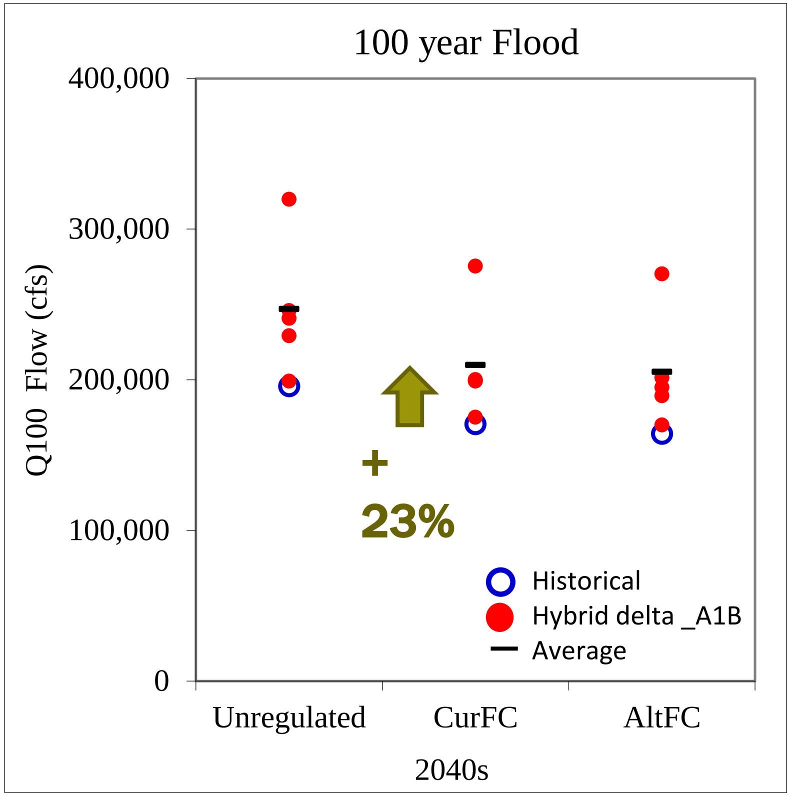

Source: Lee & Hamlet, 2012

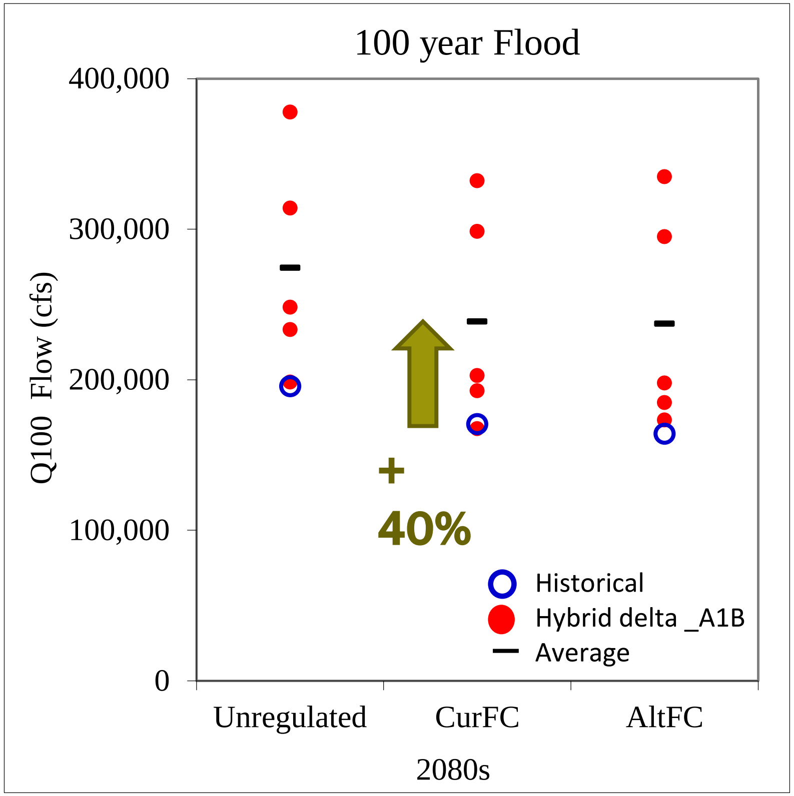
# CHANGES IN FLOODING




**Source: Tohver and Hamlet (2010)**

# CHANGES IN 100-YEAR FLOOD STATISTICS

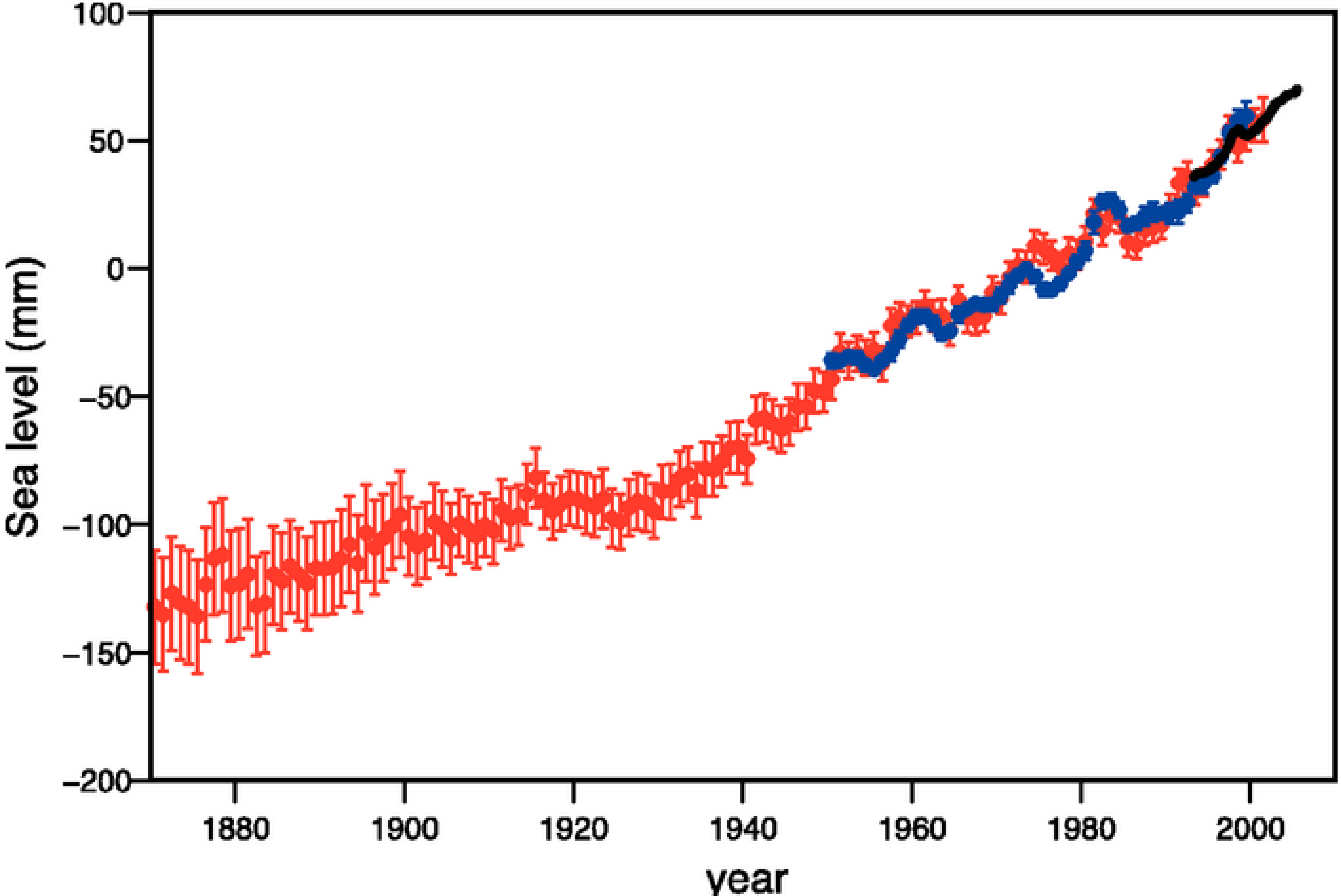



- 100-year flood risks are reduced only 3 % for the 2040s and 1 % for the 2080s under the alternative flood control curves.
- The alternative flood control operations are largely ineffective in mitigating the increased flood risks.

**Source: Lee & Hamlet, 2012**

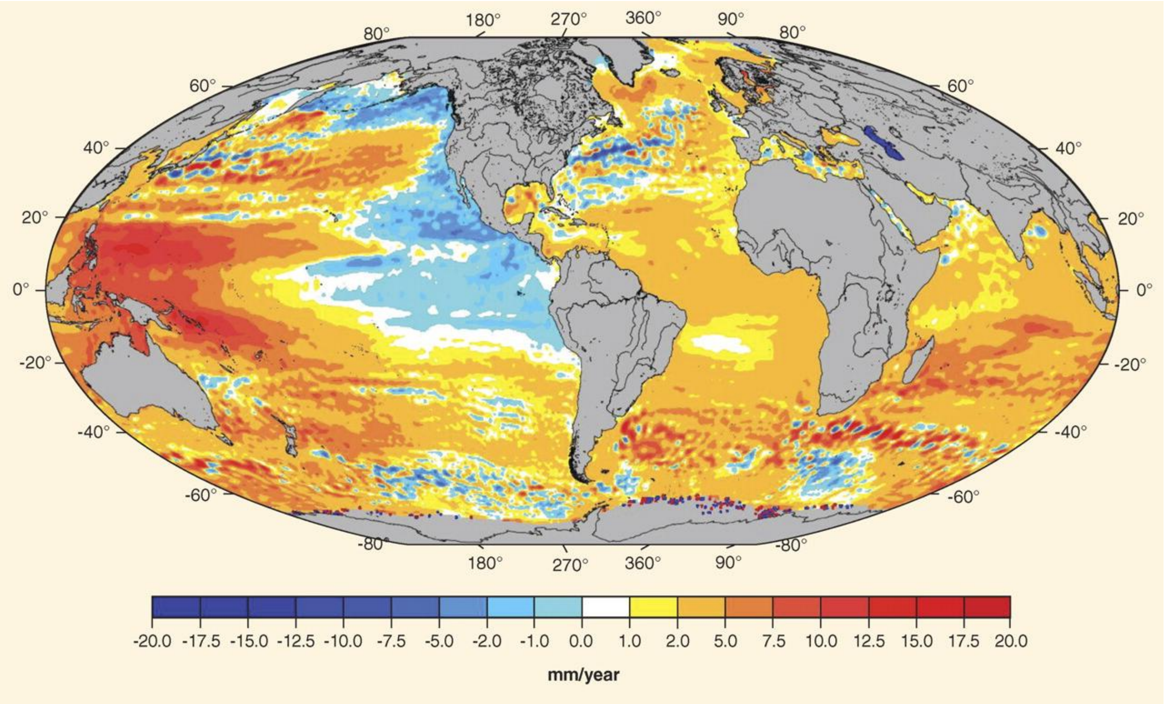
# SEA LEVEL RISE




Source: IPCC, 2007

# GLOBAL SEA LEVEL RISE

Sea-Level Trends from Satellite Altimetry, 1992 -2009

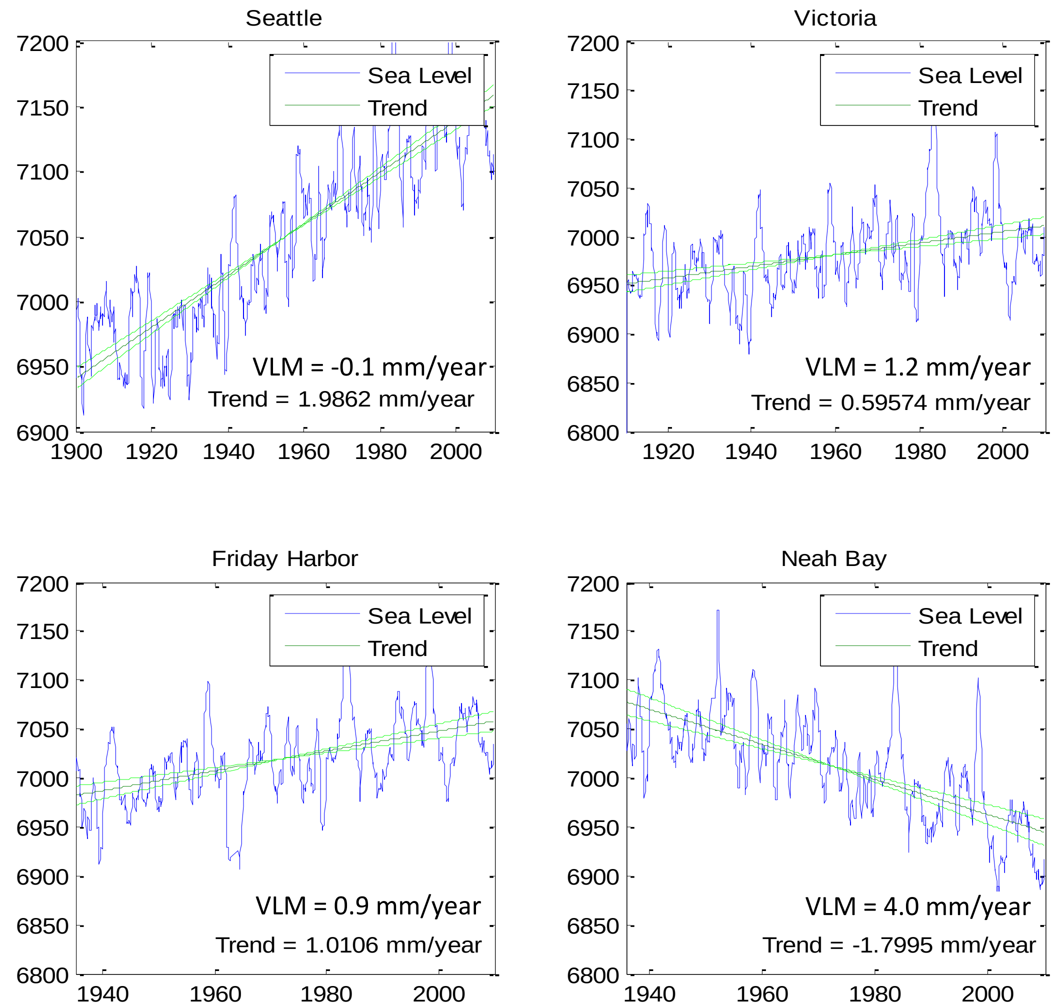



- Heterogeneous global SLR
- Observed trends in Eastern Pacific sea level are negative over past 20 years
- Likely due to large scale wind patterns
- It is unclear how long this pattern will persist

Source: Nicholls and Cazenave, 2010

# PUGET SOUND SEA LEVEL RISE

- **Puget Sound SLR rate adjusted for vertical land movement is 1.8-2.2 mm/year.**
- **Recent trends in Puget Sound MSL are smaller than 20year global average of 3.26 mm/year.**



# PROJECTIONS OF GLOBAL SEA LEVEL RISE

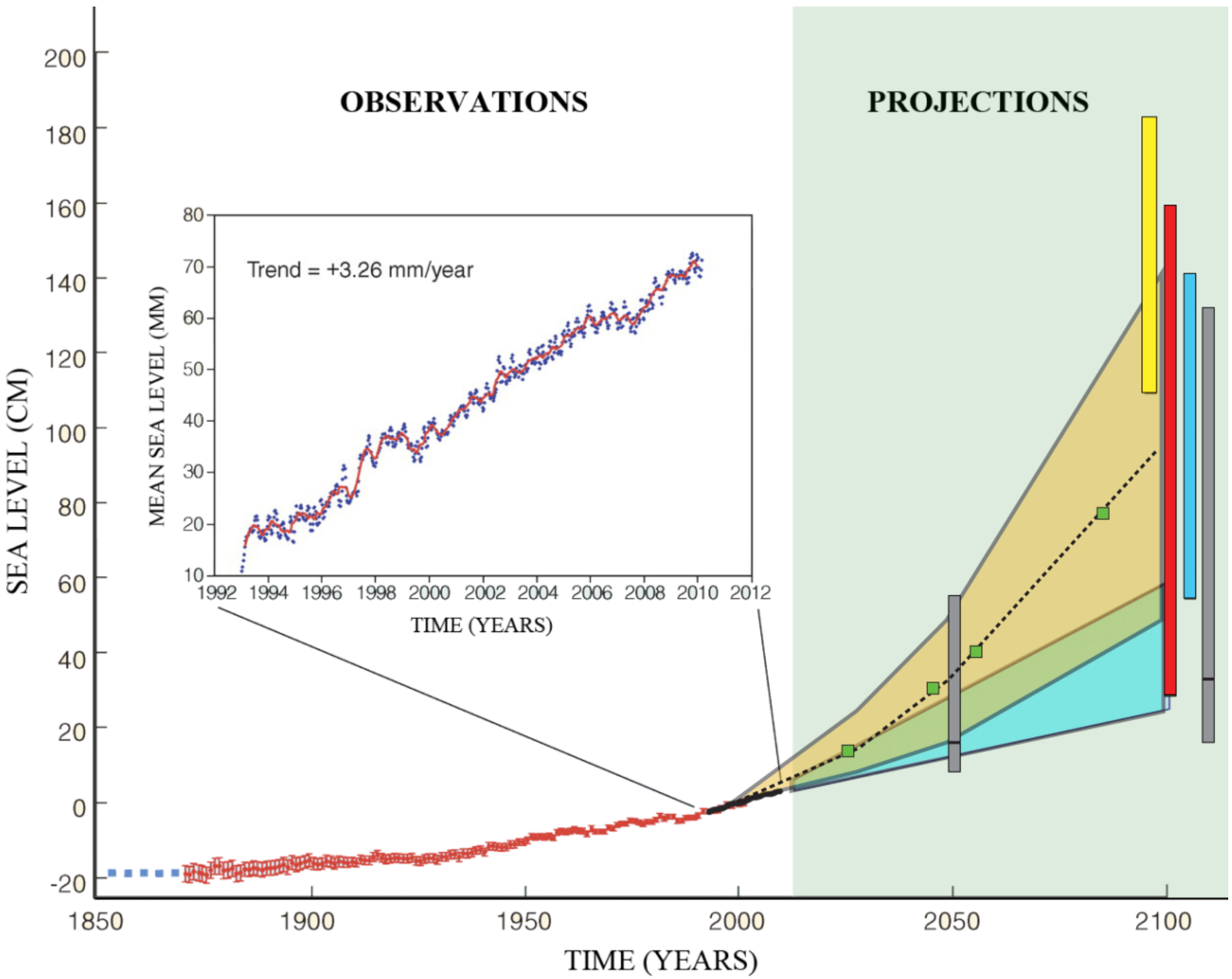
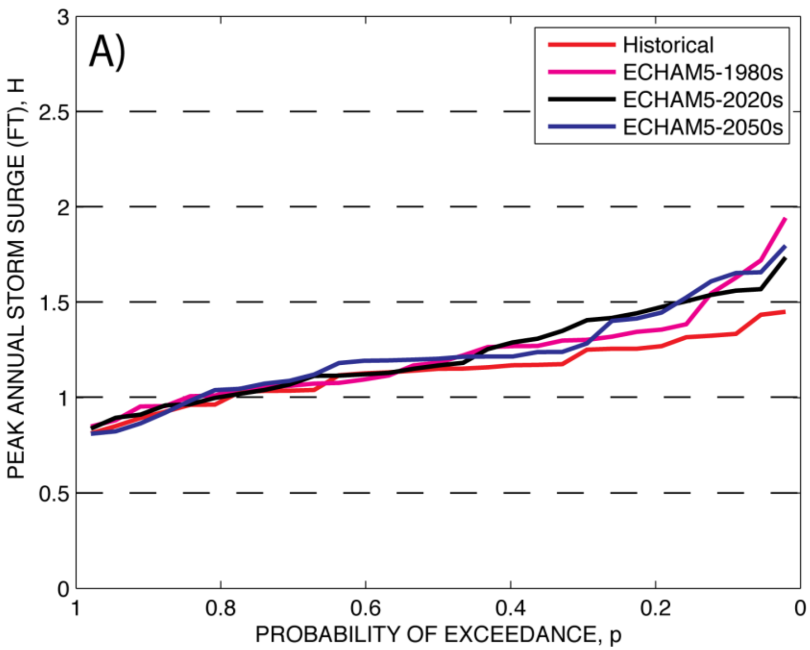
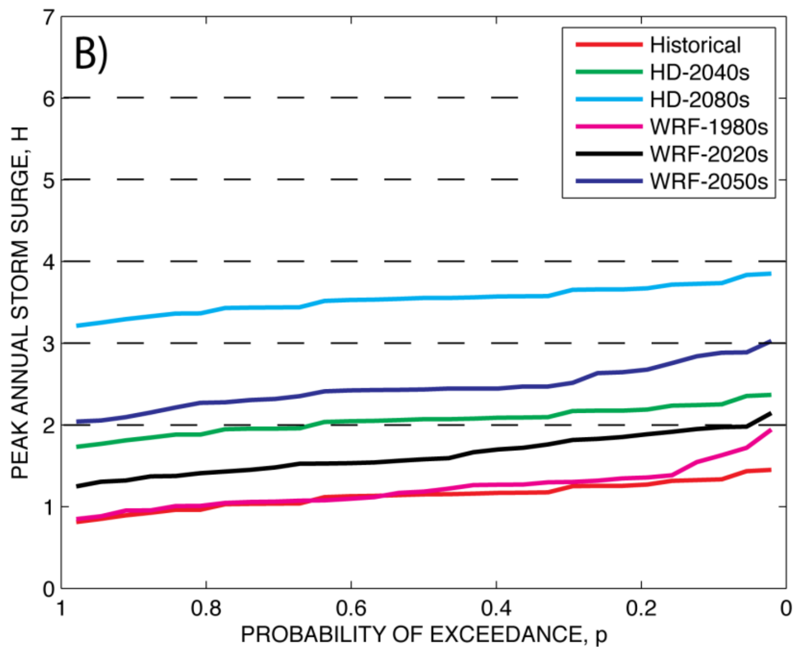



Figure adapted from Nicholls and Cazenave (2010)

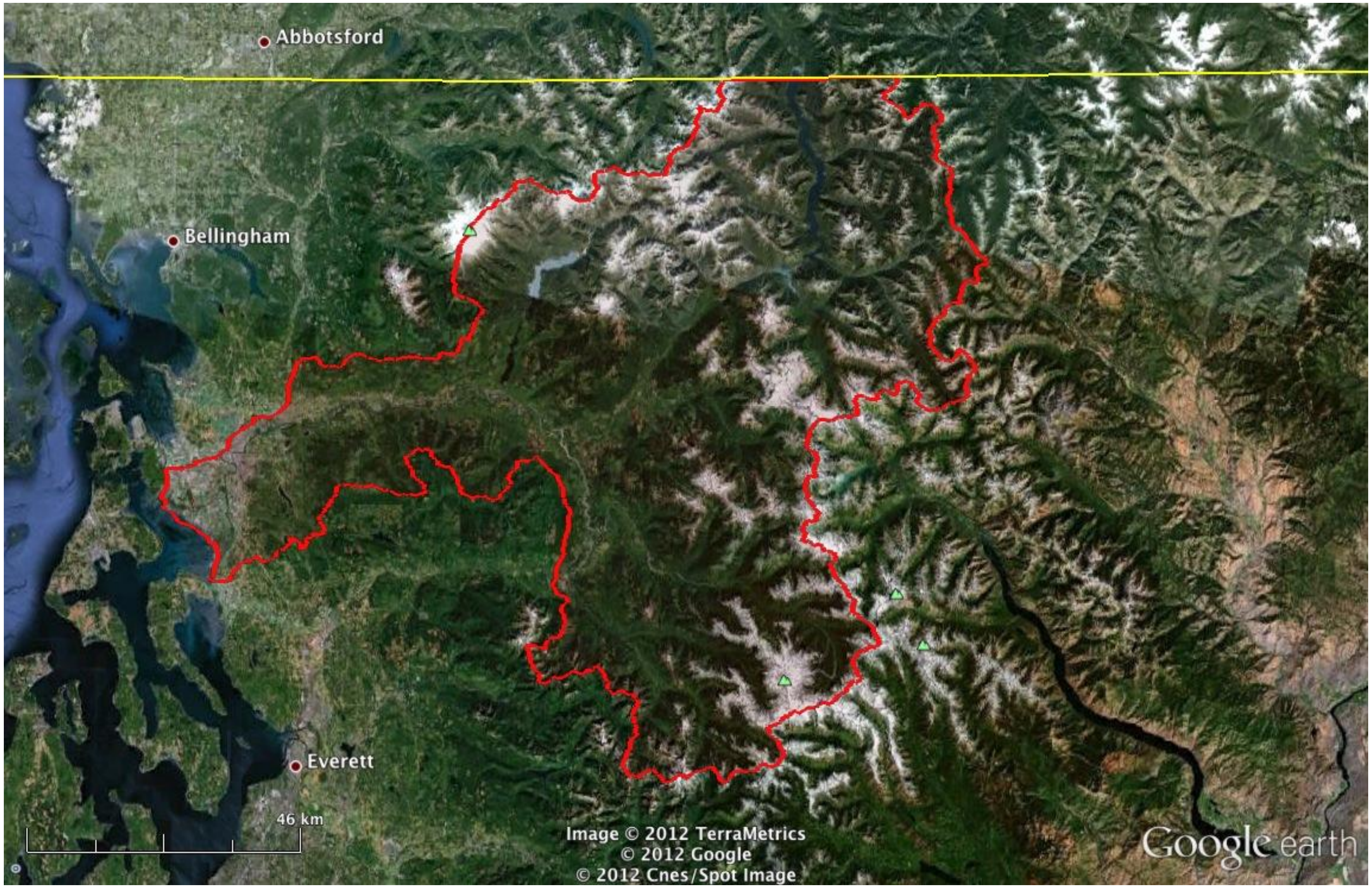
# STORM SURGE AND SLR



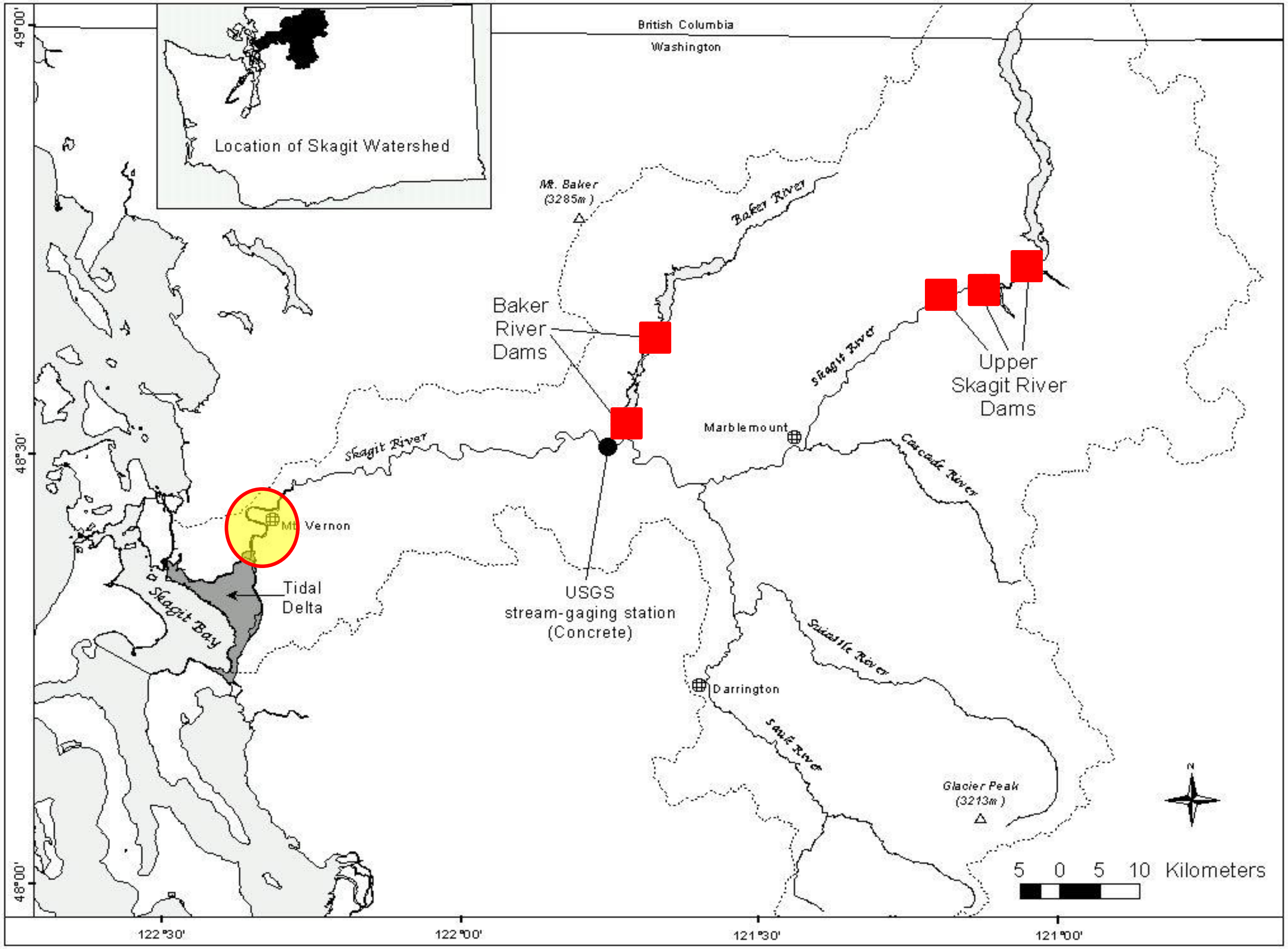




- No change in the storm surge CDFs between RCM time periods
- SLR, by comparison, drastically changes the CDFs by shifting them each upward

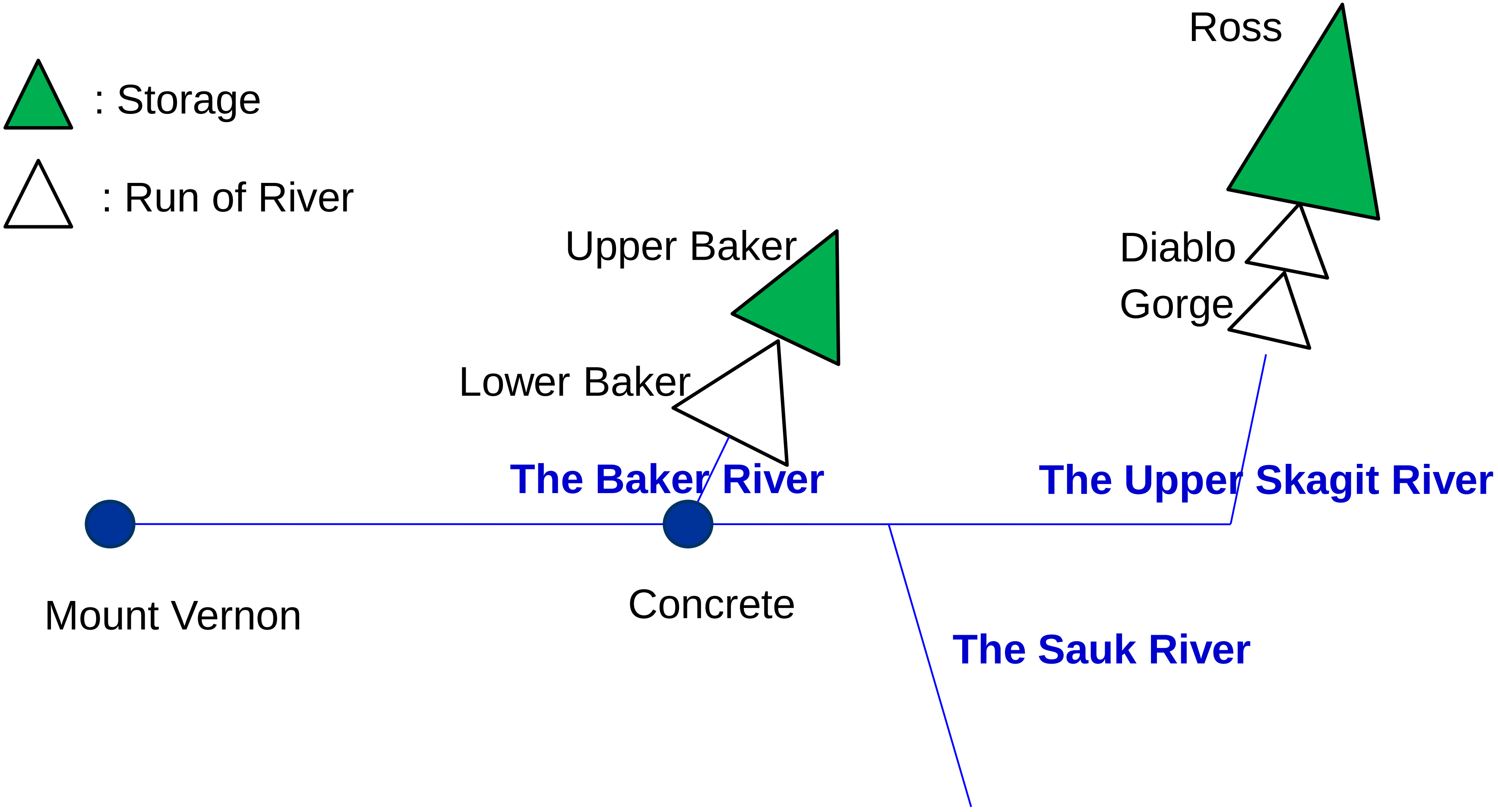
# SKAGIT RIVER BASIN



# SKAGIT RIVER BASIN

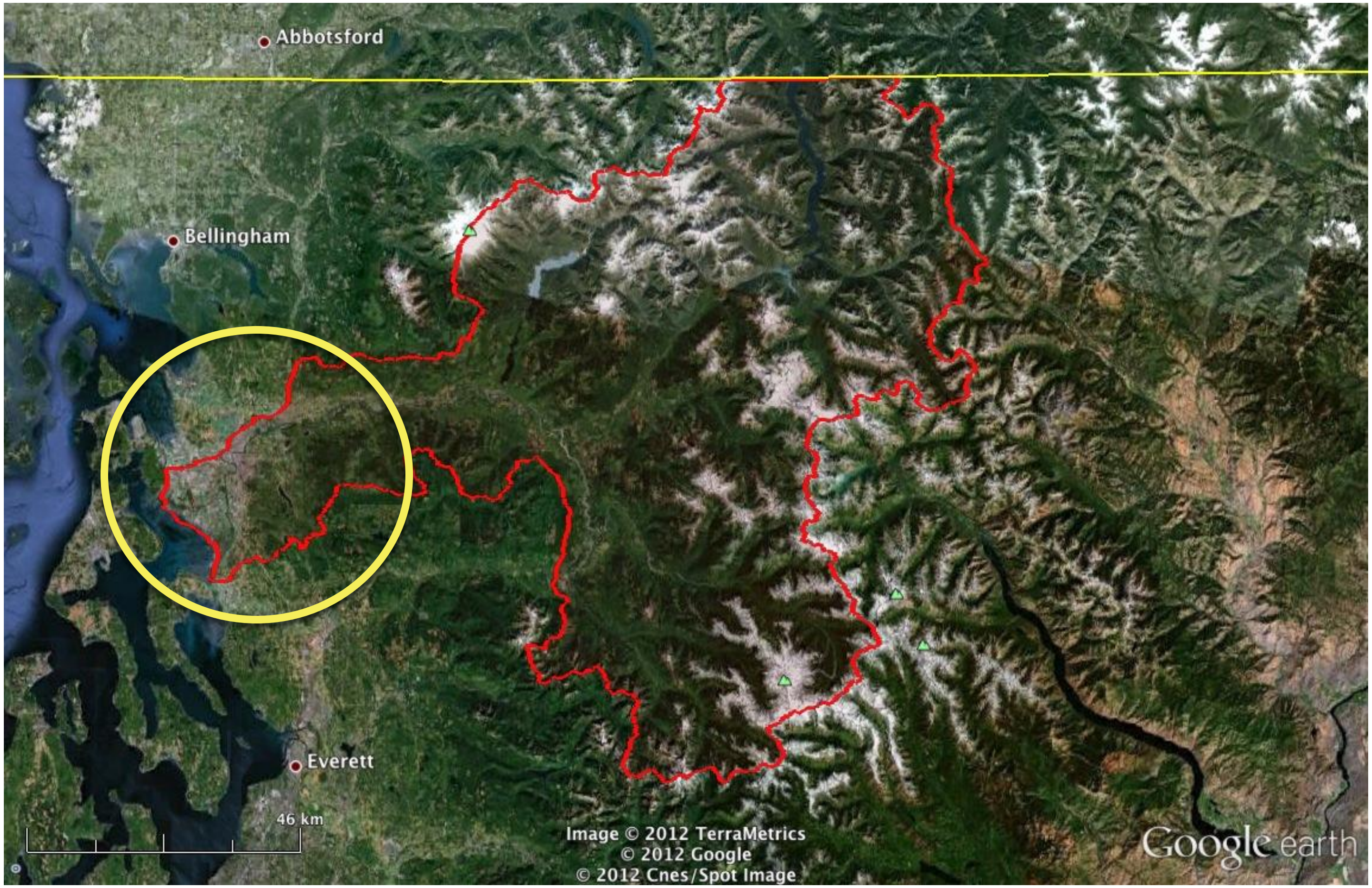


# THE SKAGIT RIVER RESERVOIRS

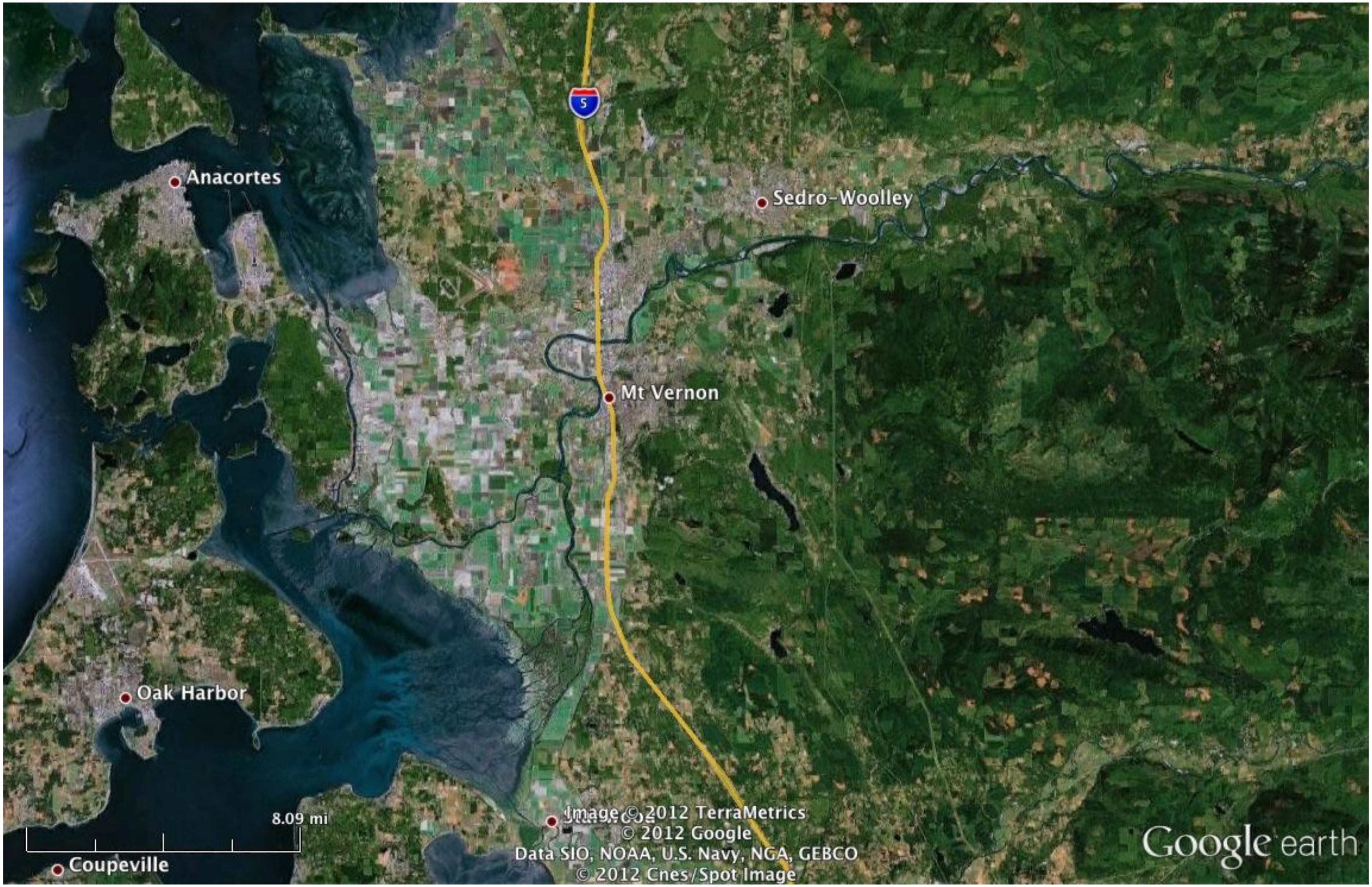



**Source: Se-Yeun Lee**

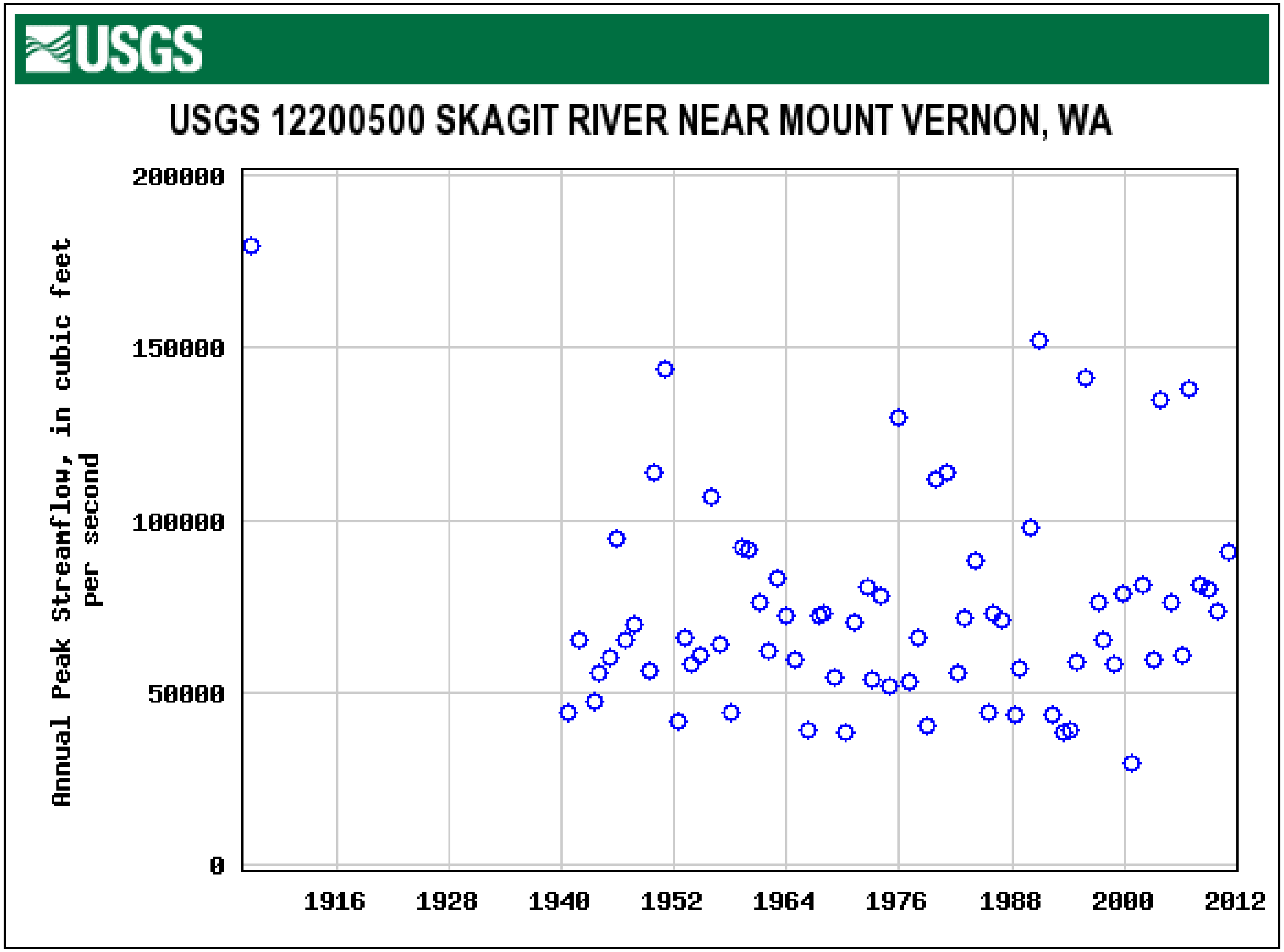
# LOWE SKAGIT RIVER BASIN



# LOWER SKAGIT RIVER BASIN



# OBSERVED FLOOD EVENTS

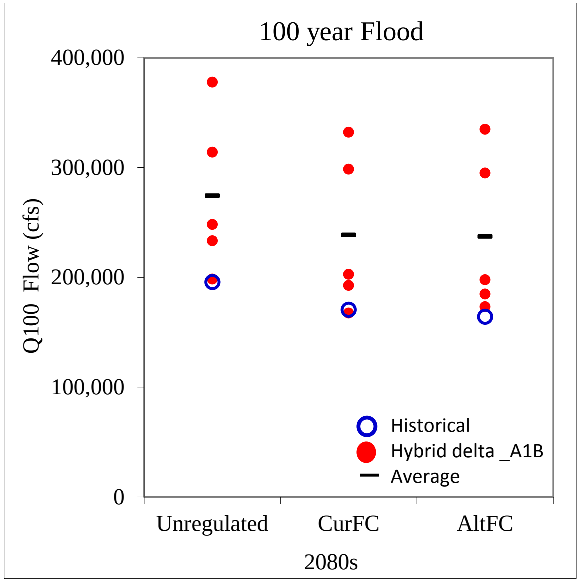


# FLOODING IN THE SKAGIT RIVER BASIN

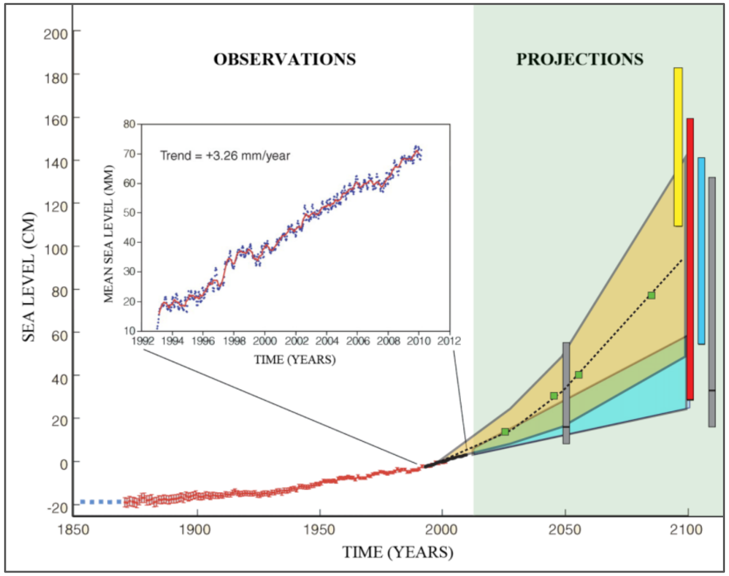
- Organizations involved:
  - US Army Corps of Engineers – Flood Control Operations
  - FEMA – Flood Mapping and Flood Insurance (NFIP)
  - Skagit County – Coordination and Development
  - Puget Sound Energy – Baker River Reservoirs
  - Seattle City Light – Skagit River Reservoirs

# LOCAL IMPACTS

- How do we combine what we know about flooding and SLR in the Skagit River to plan for the future?



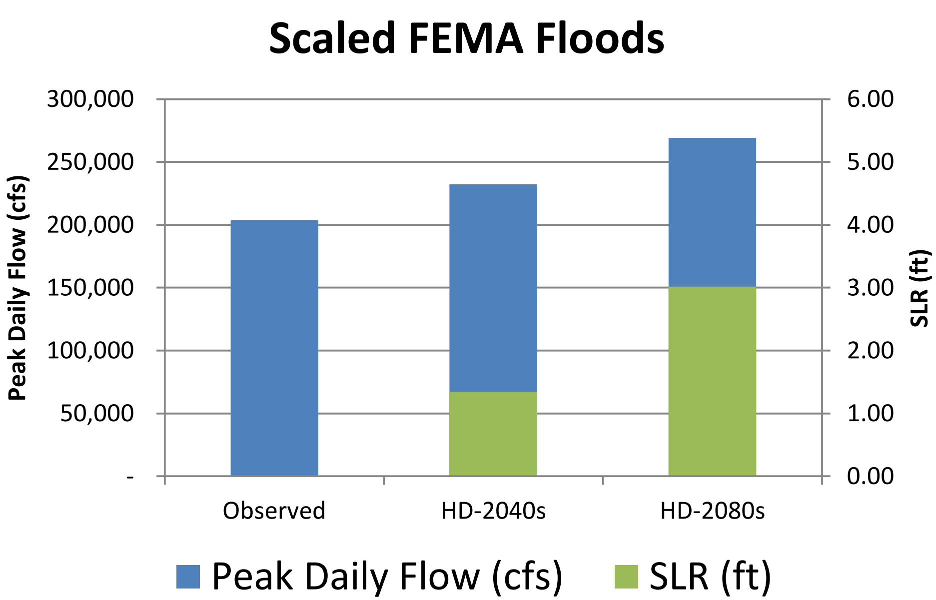

+

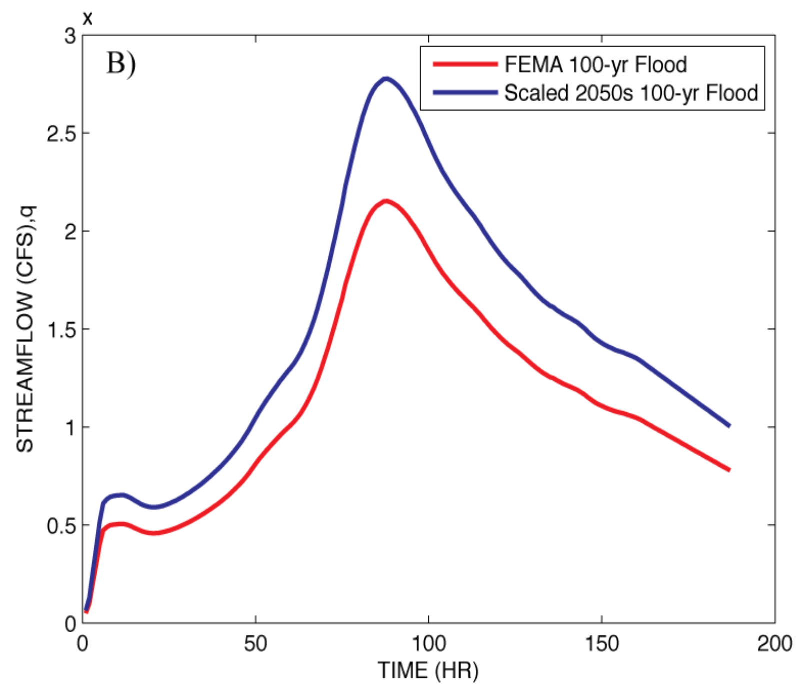


# METHODS
## 100-YEAR FLOOD MAPPING

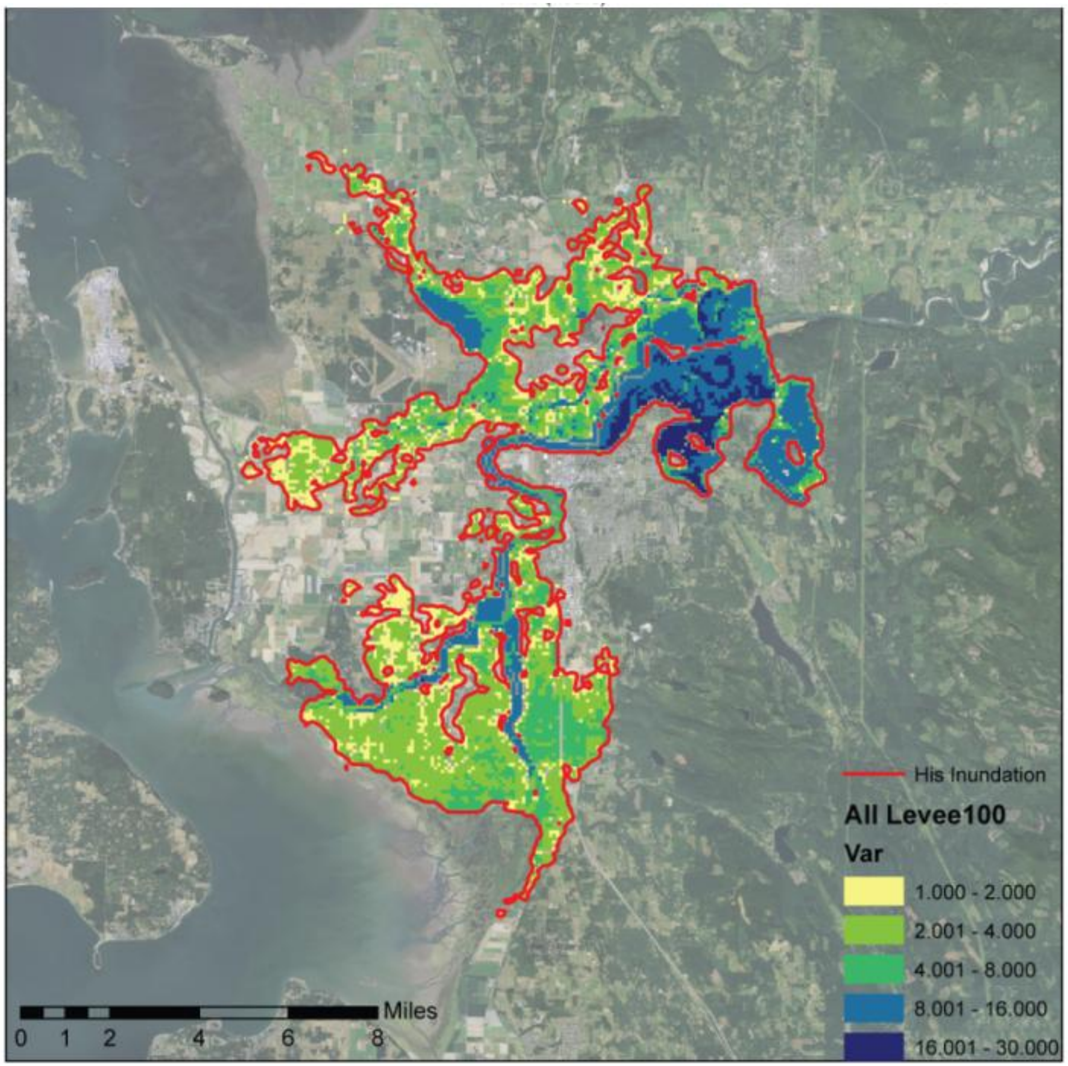
- Applied relative changes in 100-year flood to FEMA hydrograph
- Eliminates model bias in peak flows
- Performed composite flood mapping for 2040s and 2080s
  (7 levee failure scenarios)

$$FEMA_{2040s} = FEMA \times \frac{100yrHD_{2040s}}{100yrHis}$$

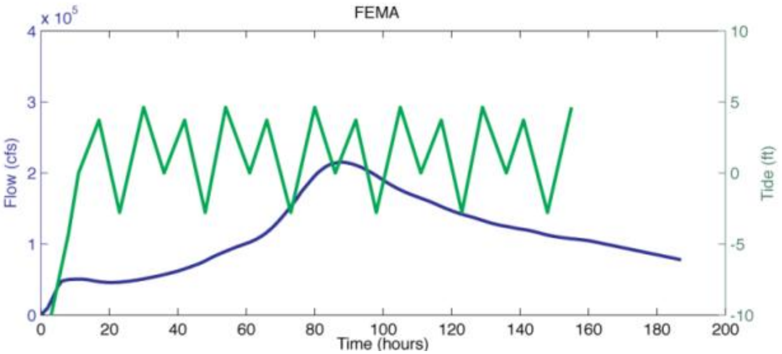


# HISTORICAL 100-YEAR FLOOD
## ALL LEVEES INTACT

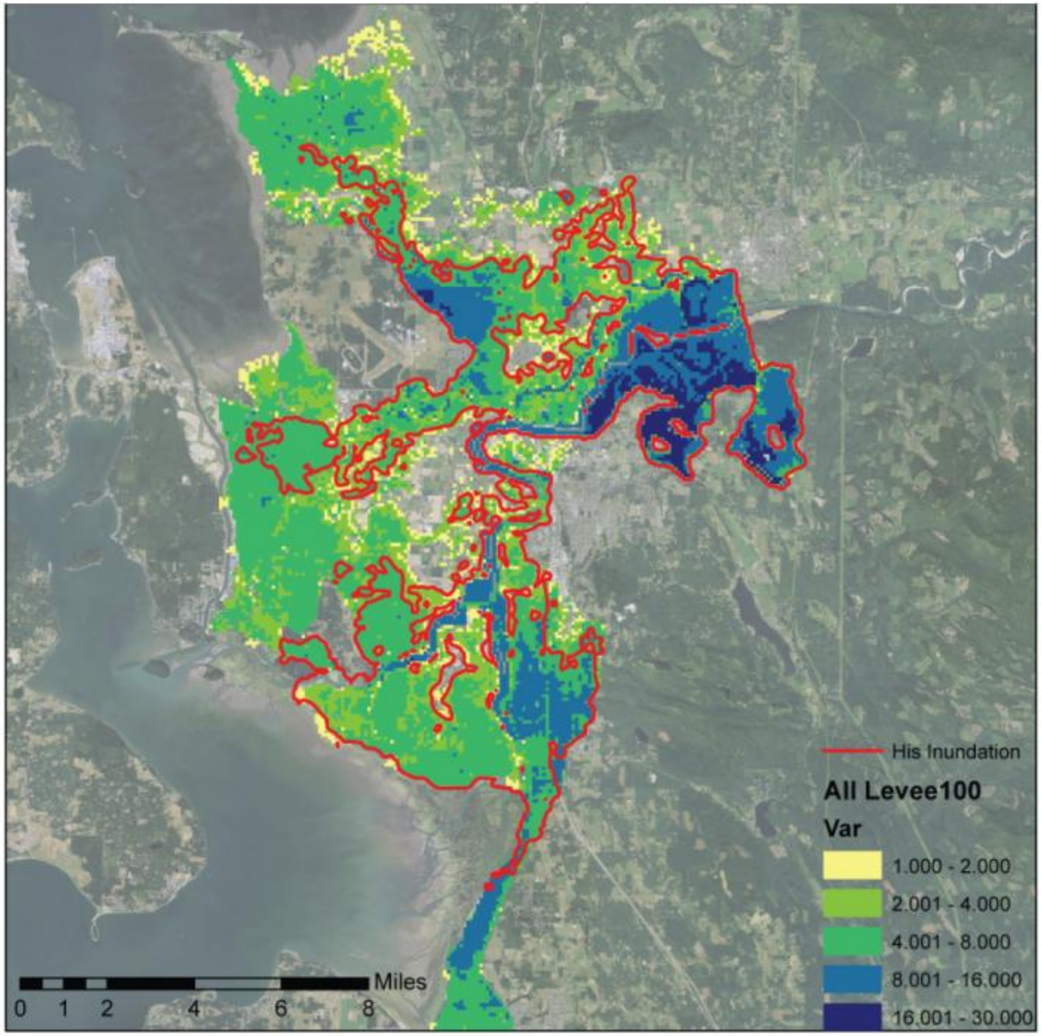



**Inputs:**
- Hydrograph: Historical 100yr
- Sea Level Rise: 0.00 feet



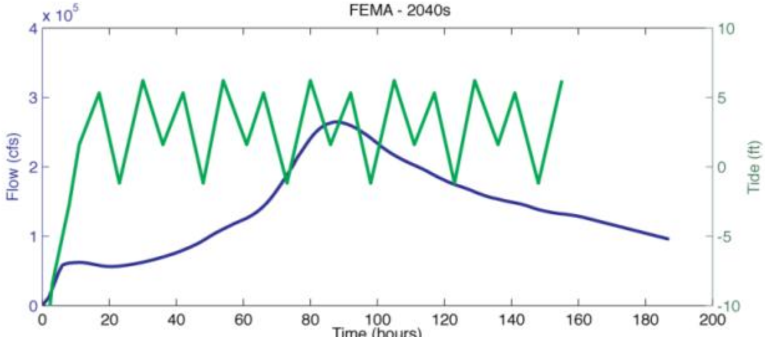

**Area Flooded:** 42,266 acres

# 2040S 100-YEAR FLOOD
## ALL LEVEES INTACT



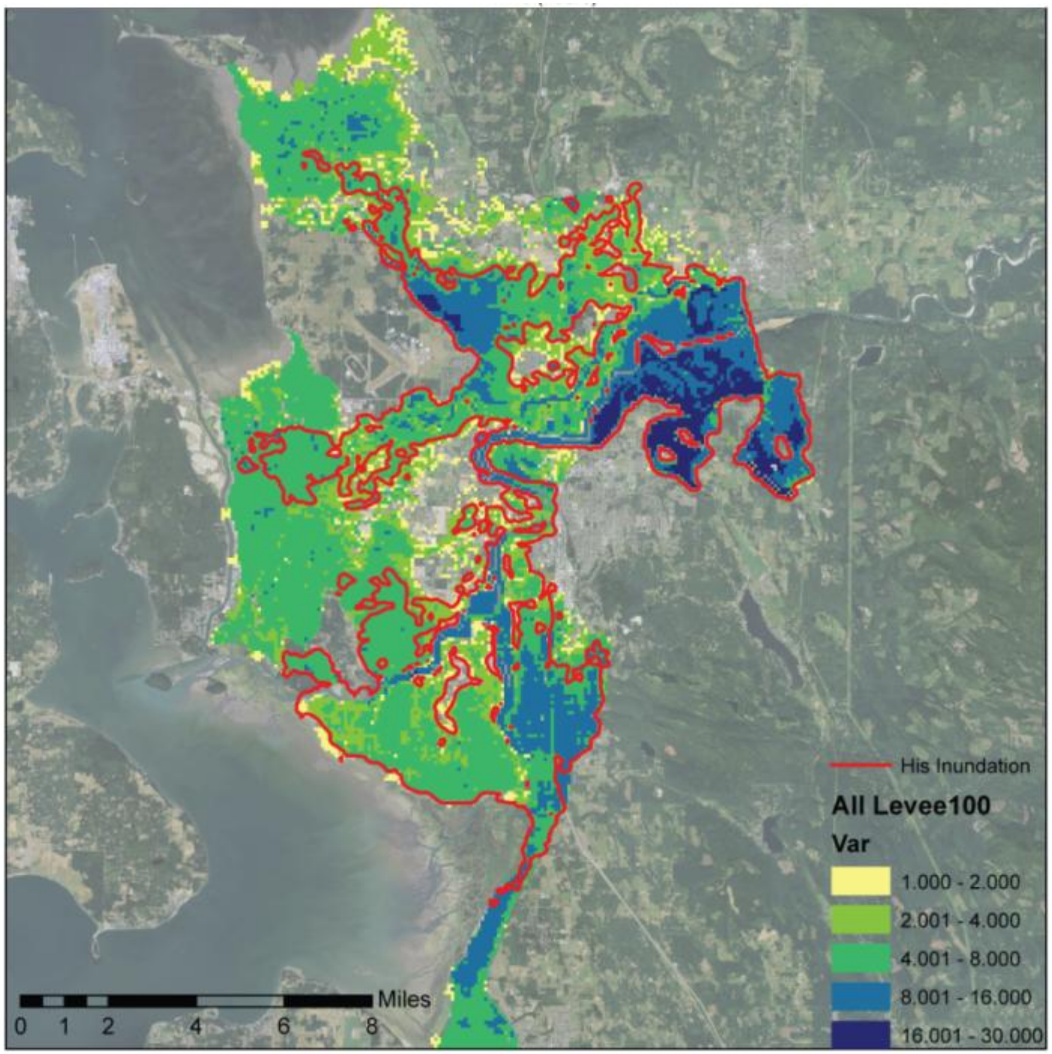

**Inputs:**

- Hydrograph: 1.14 x (His 100yr)
- Sea Level Rise: 1.35 feet

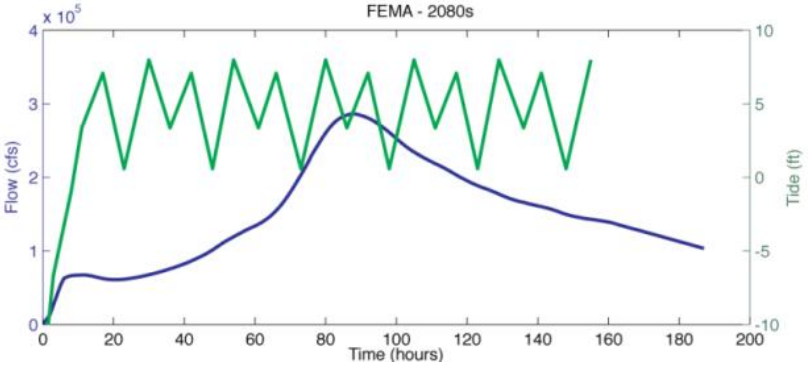



**Area Flooded:** 66,248 acres (+57%)

# 2080S 100-YEAR FLOOD
## ALL LEVEES INTACT



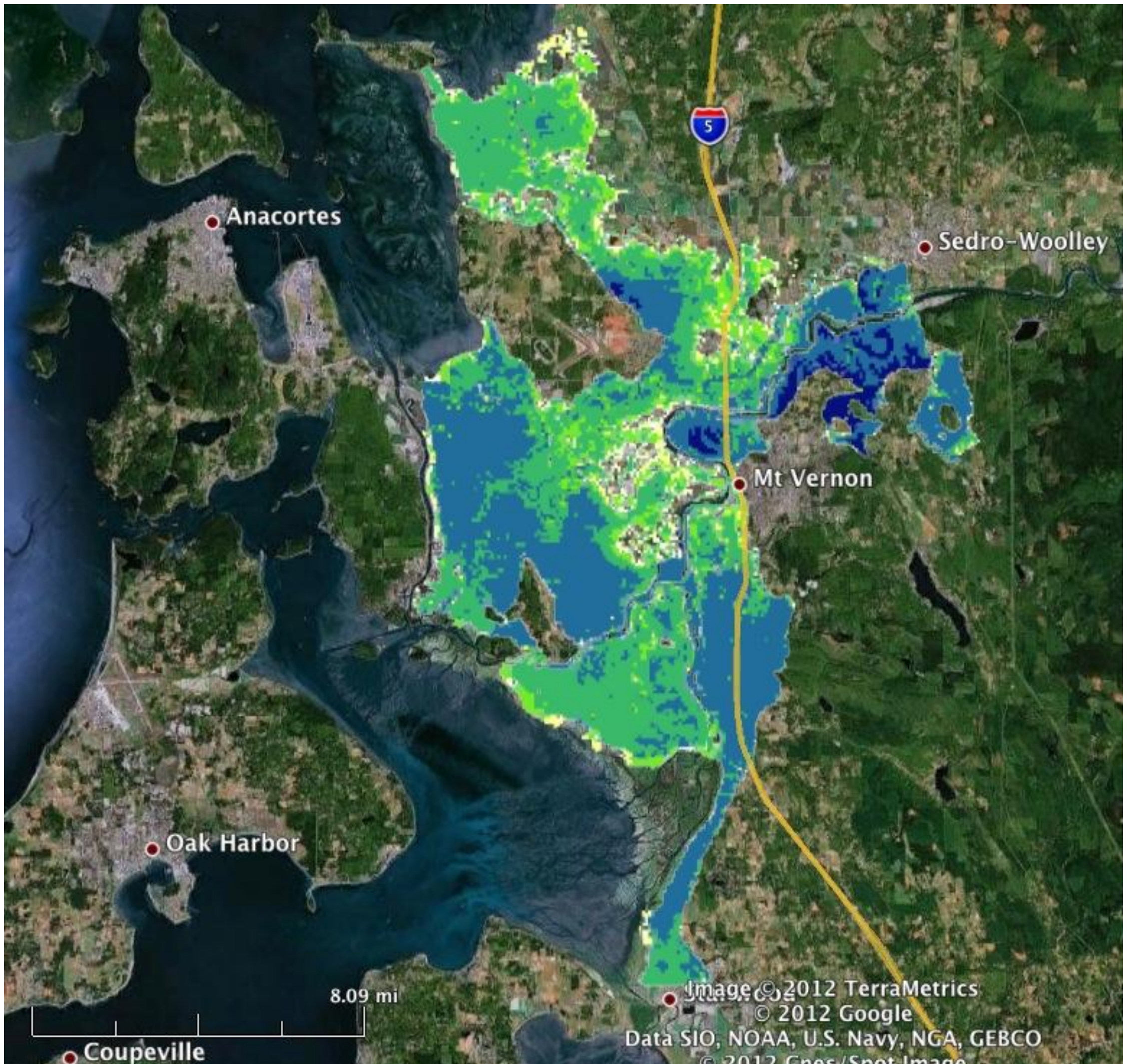

**Inputs:**
- Hydrograph: 1.32 x (His 100yr)
- Sea Level Rise: 3.02 feet




**Area Flooded**: 73,594 acres (+74%)

# COMPOSITE FLOOD MAPS

## HISTORICAL




**Inputs:**

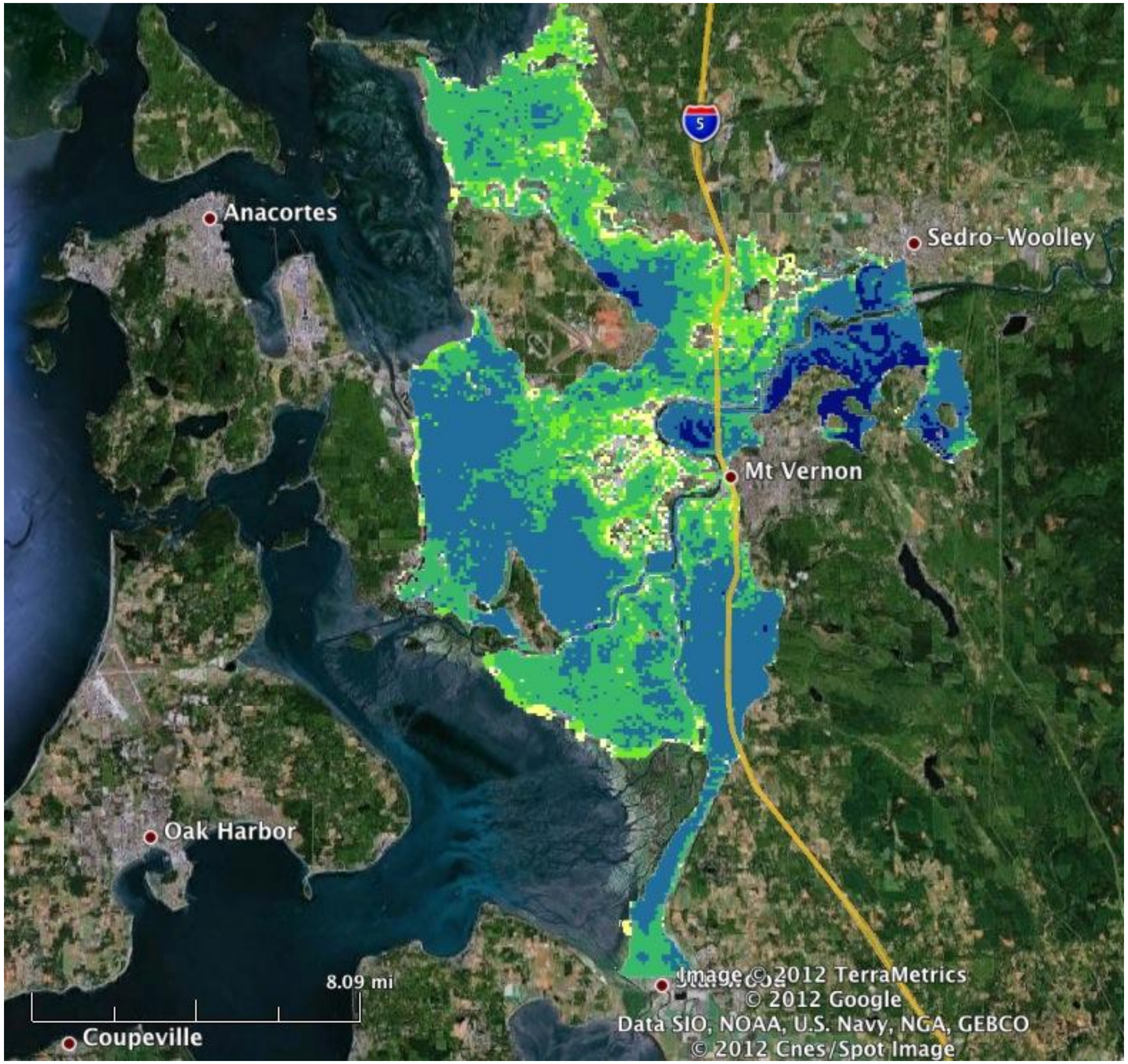
- Hydrograph: Historical 100yr
- Sea Level Rise: 0.00 feet

**Area Flooded**: 71,427 acres

**Avg Depth**: 7.03 feet

1.000 - 2.000
2.001 - 4.000
4.001 - 8.000
8.001 - 16.000
16.001 - 30.000

# COMPOSITE FLOOD MAPS
## 2040S




**Inputs:**

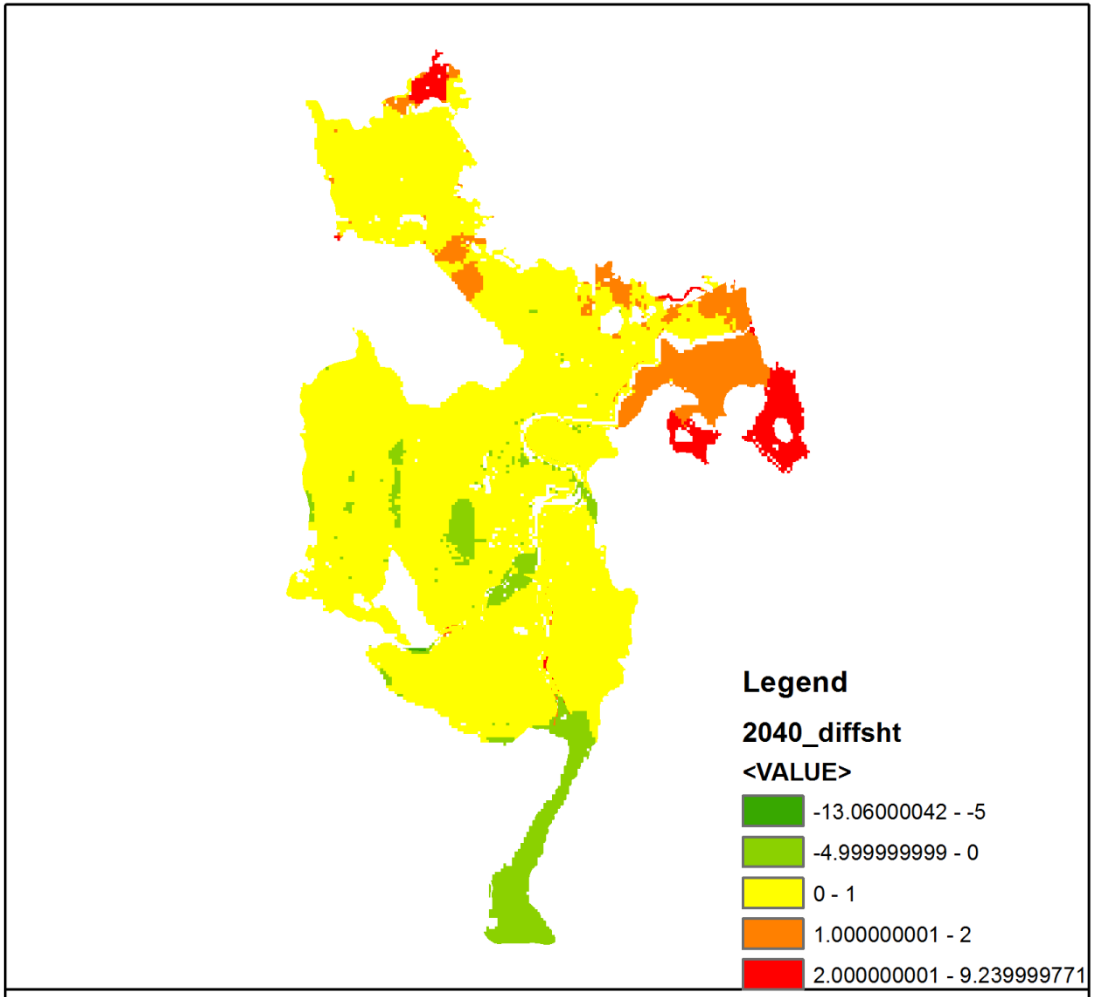
- Hydrograph: 1.14 x (His 100yr)
- Sea Level Rise: 1.35feet

**Area Flooded**: 72,206 acres (+1%)

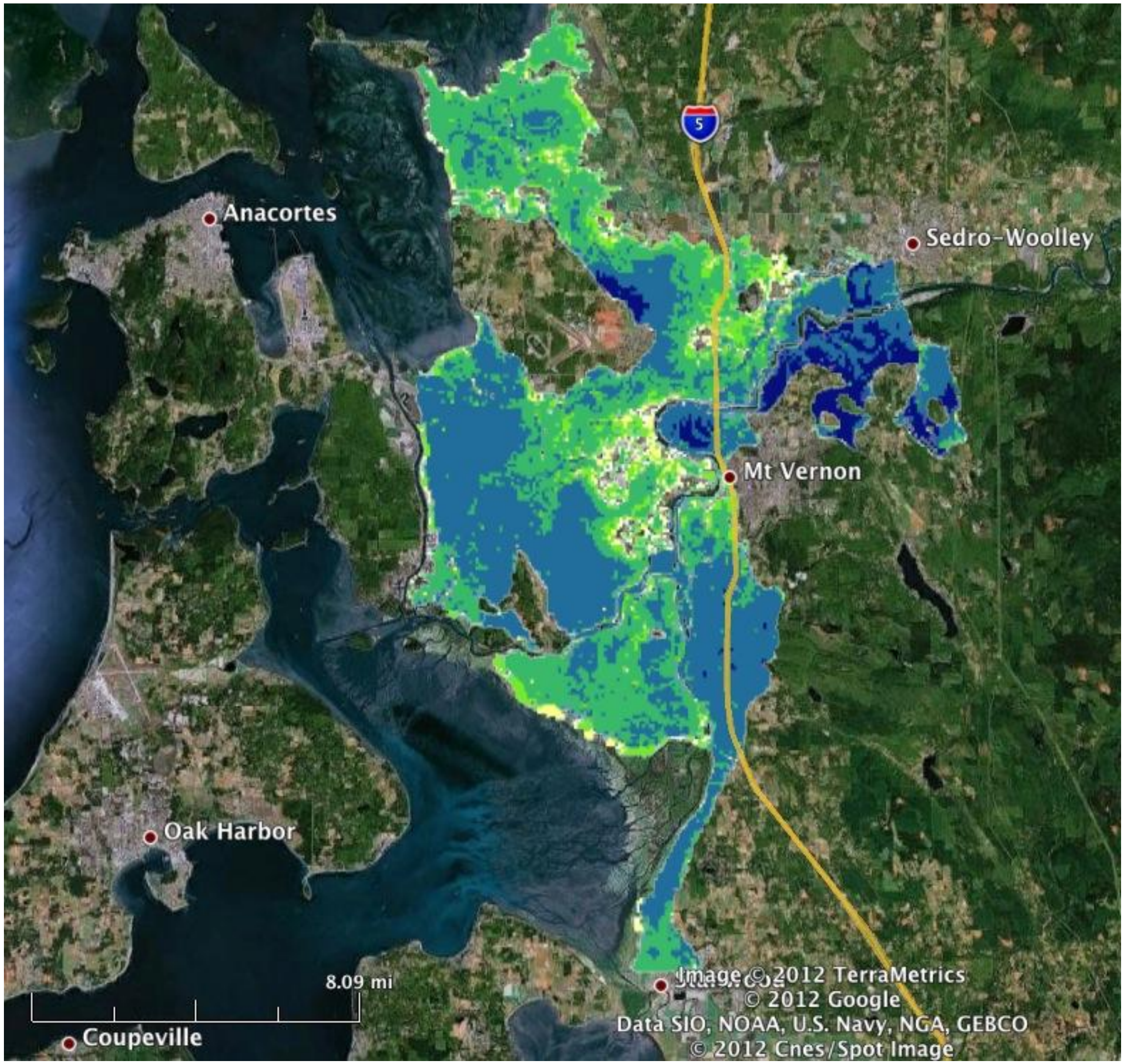
**Avg Depth**: 7.46 feet (+5 inches)

| | |
|---|---|
| (yellow) | 1.000 - 2.000 |
| (light green) | 2.001 - 4.000 |
| (green) | 4.001 - 8.000 |
| (blue) | 8.001 - 16.000 |
| (dark blue) | 16.001 - 30.000 |

# COMPOSITE FLOOD MAPS
## 2040S



# COMPOSITE FLOOD MAPS
## 2080S




**Inputs:**

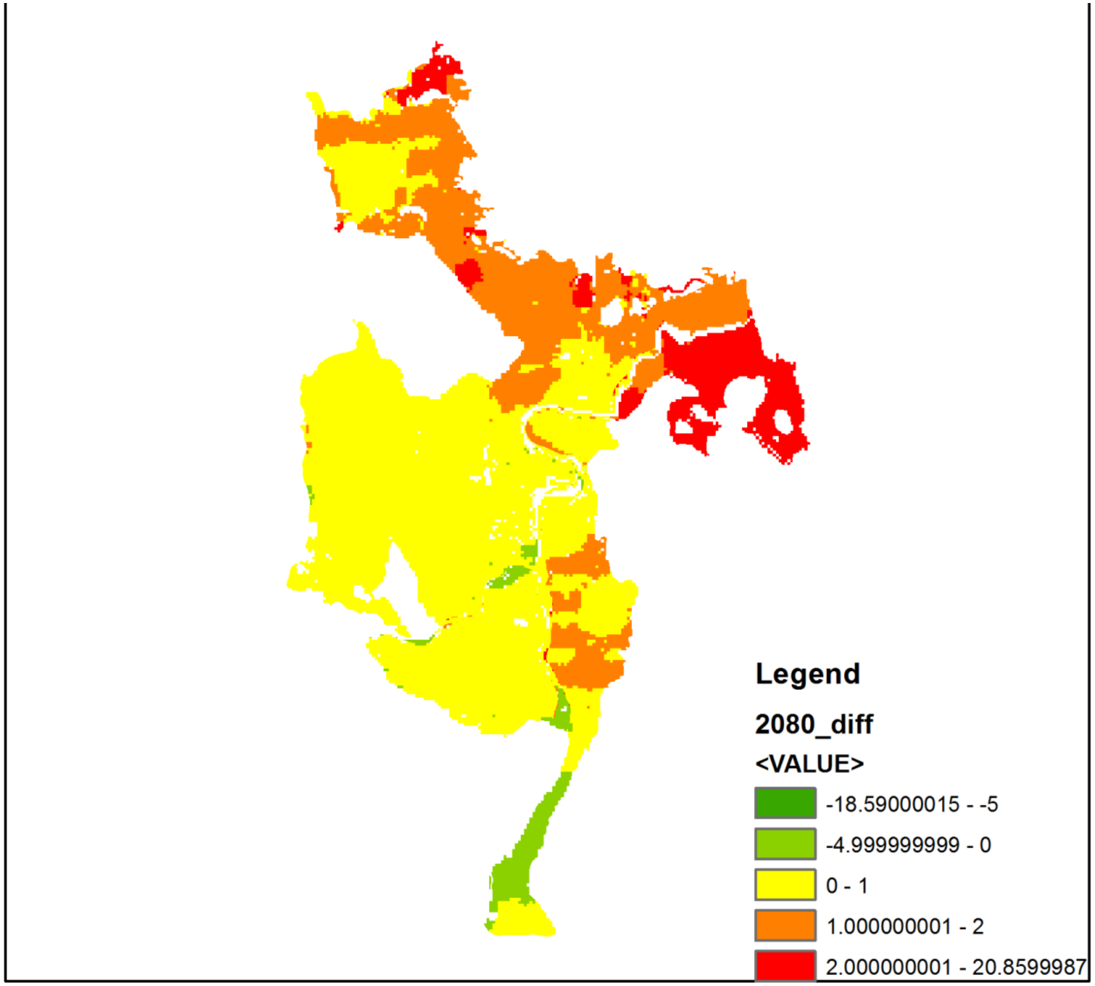
- Hydrograph: 1.32 x (His 100yr)
- Sea Level Rise: 3.02 feet

**Area Flooded**: 72,768 acres (+2%)

**Avg Depth**: 7.46 feet (+10 inches)

1.000 - 2.000
2.001 - 4.000
4.001 - 8.000
8.001 - 16.000
16.001 - 30.000

# COMPOSITE FLOOD MAPS
## 2080S



# CONCLUSIONS

- Future storm surge, brought on by barometric and wind effects, is not expected to change significantly.
- Sea level rise is expected to influence extreme water levels much more than changes in storm surge.
- Inundation from flooding in the Skagit is expected to increase by up to 74% by the 2080s given combined SLR and increased flood magnitudes.
- Average depth in flood map increases by
  - 5 inches in 2040s
  - 10 inches in 2080s
- Using a scenario based approach is an effective way to understand changes in flood magnitudes over time.

# RESOURCES

- Skagit County HAZUS - http://www.skagitcounty.net/Common/asp/default.asp?d=PlanningAndPermit&c=General&p=FEMAfloodstudy/femafloodstudy2010.htm
- Skagit County Flood Study – http://www.skagitcounty.net/Common/asp/default.asp?d=PlanningAndPermit&c=General&p=FEMAfloodstudy.htm
- Envision Skagit 2060 - http://www.skagitcounty.net/Common/asp/default.asp?d=EnvisionSkagit&c=General&P=reports.htm
- Climate Impacts Group, 2860 project - http://www.hydro.washington.edu/2860/

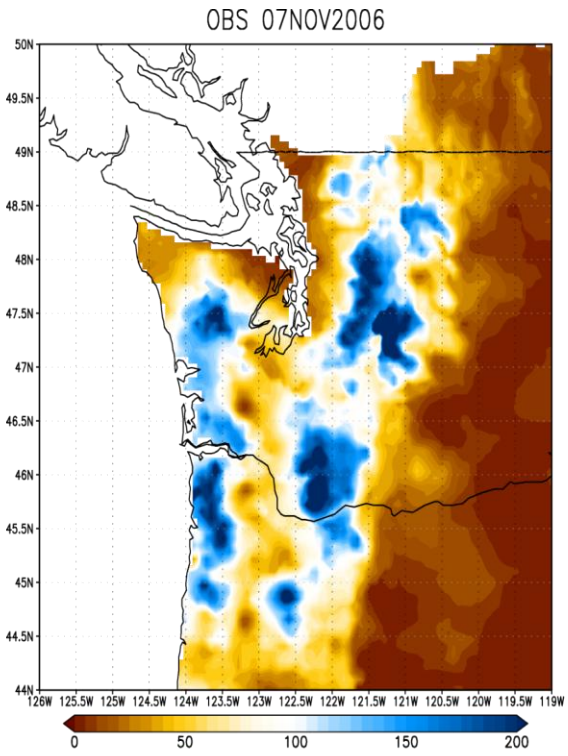
# QUESTIONS?

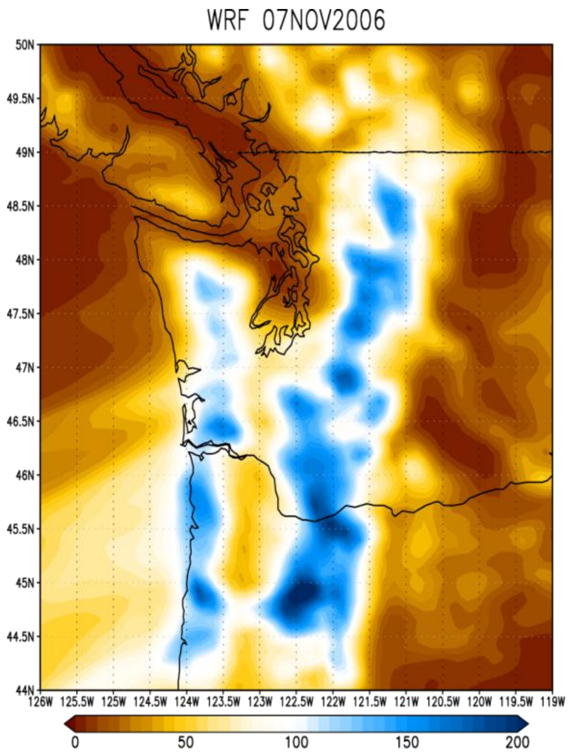
Acknowledgments

- Alan Hamlet, Faculty Advisor
- Contributors
  - Se-Yuen Lee
  - Matt Stumbaugh
  - Eric Salathé
- EPA Funding
  - Roger Fuller
  - Eric Grossman

# EXTRAS

# DYNAMIC DOWNSCALING

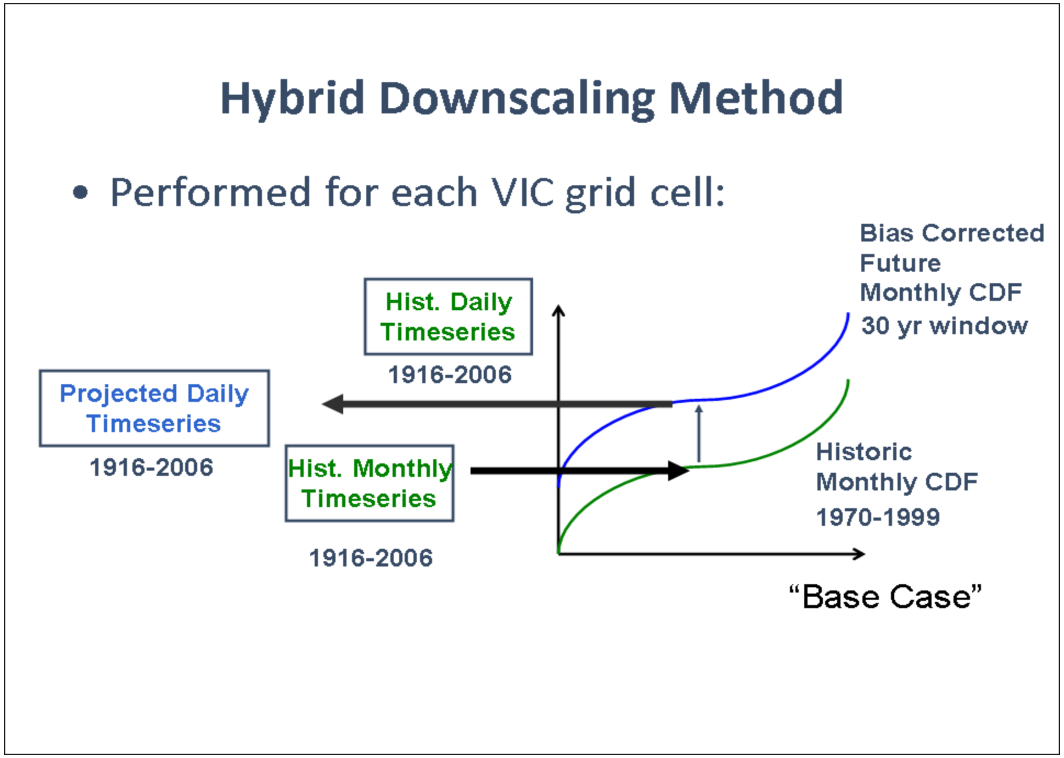



- WRF provides atmospheric conditions at much higher resolution
- Simulates actual weather prescribed by large scale GCM
- Produces actual storms
- Does not rely on the historical time series

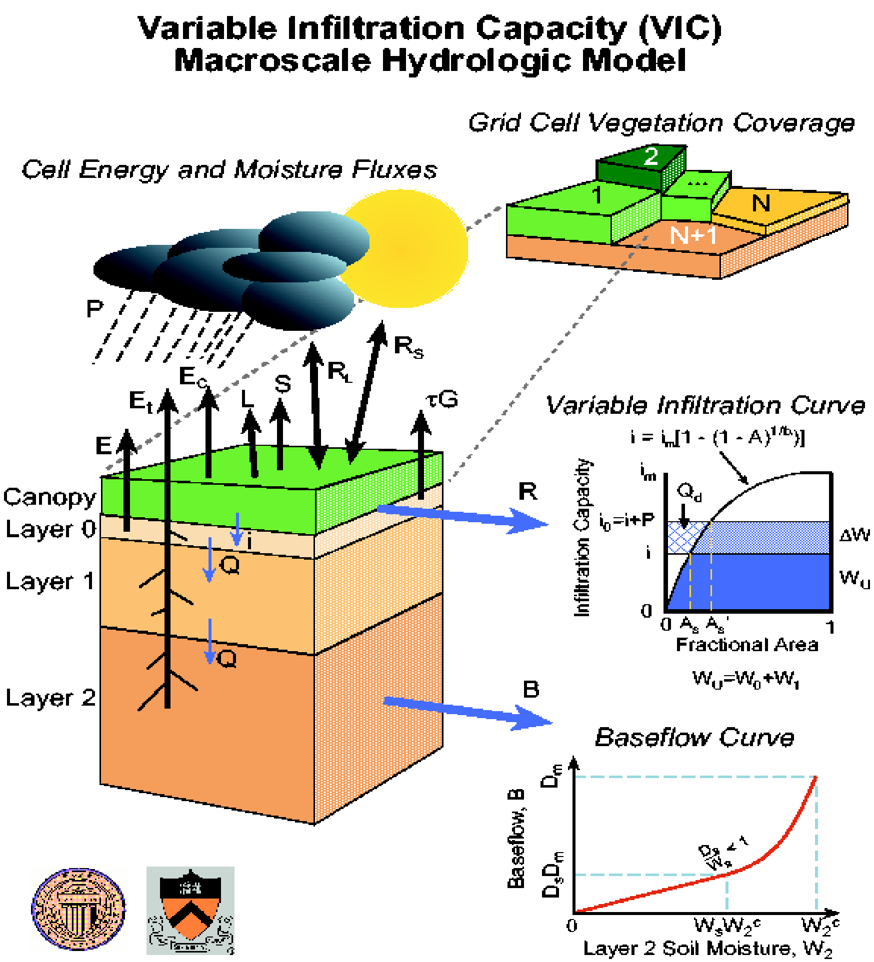
- Three 30-year time periods
  - 1980s, 2020s and 2050s

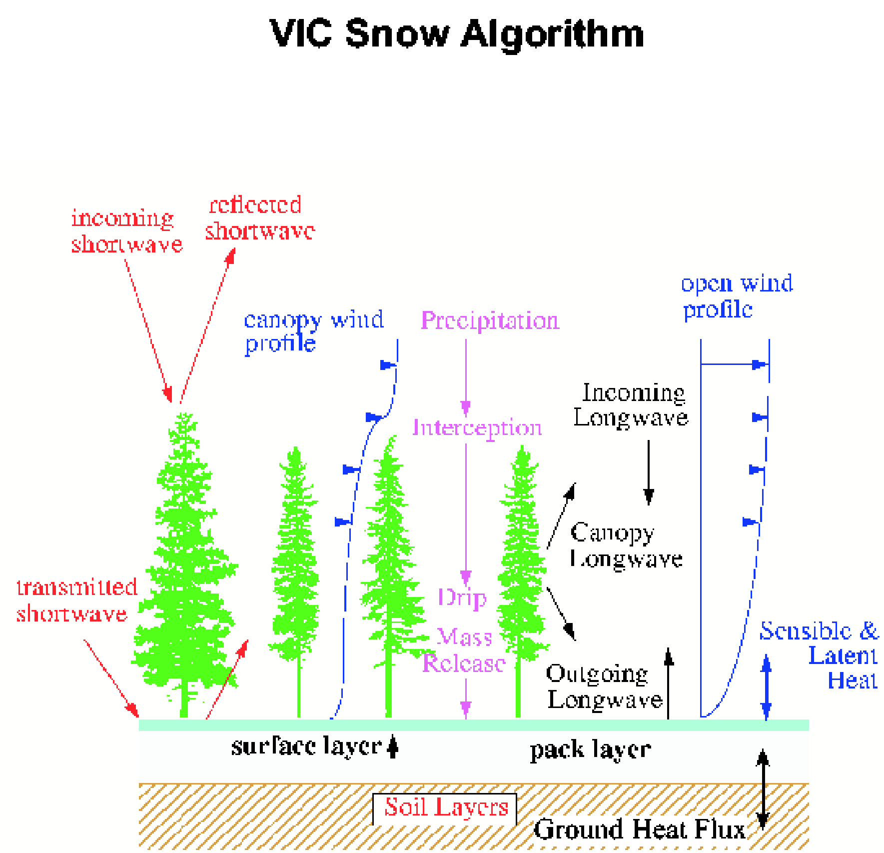
# STATISTICAL DOWNSCALING



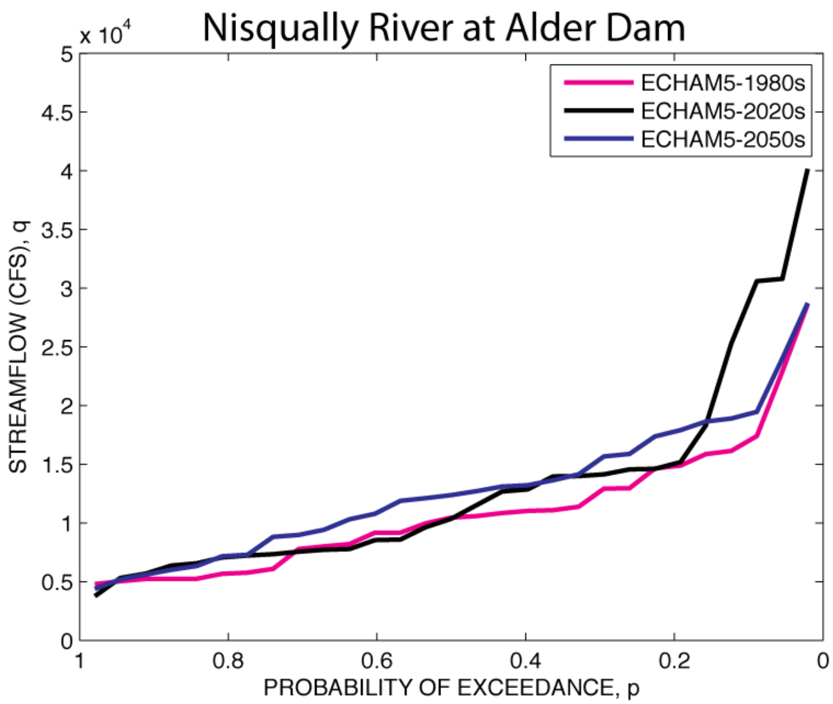

- Adjusts historic monthly timeseries to match CDF of GCM at each grid cell
- Forces historic daily timeseries to fit new monthly values
- Preserves most of the historical time series behavior
  - Storm size, storm location, interarrival, seasonality, time, etc.
- Two30-year time periods
  - 2040s and 2080s

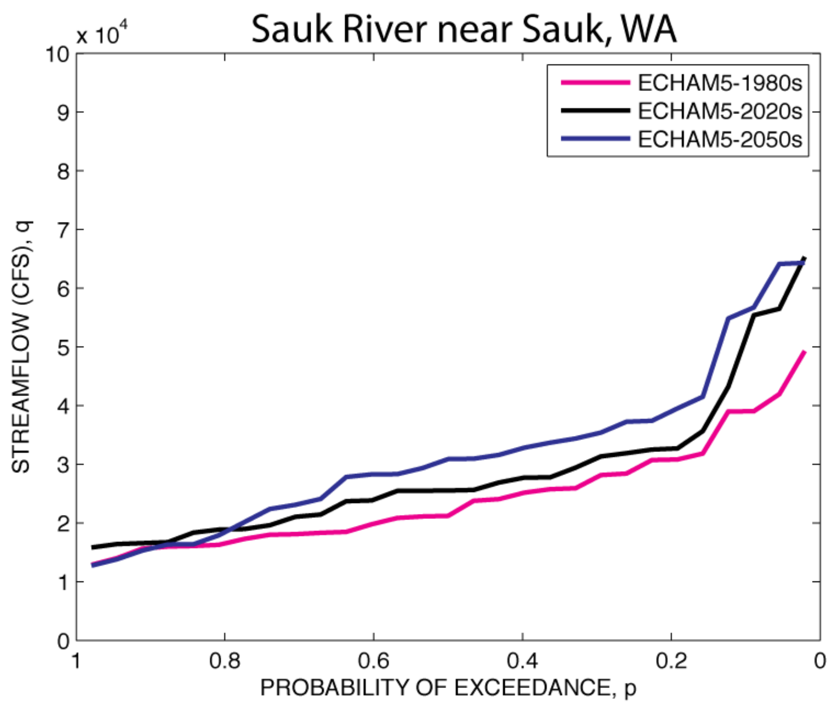
# HYDROLOGIC MODELING



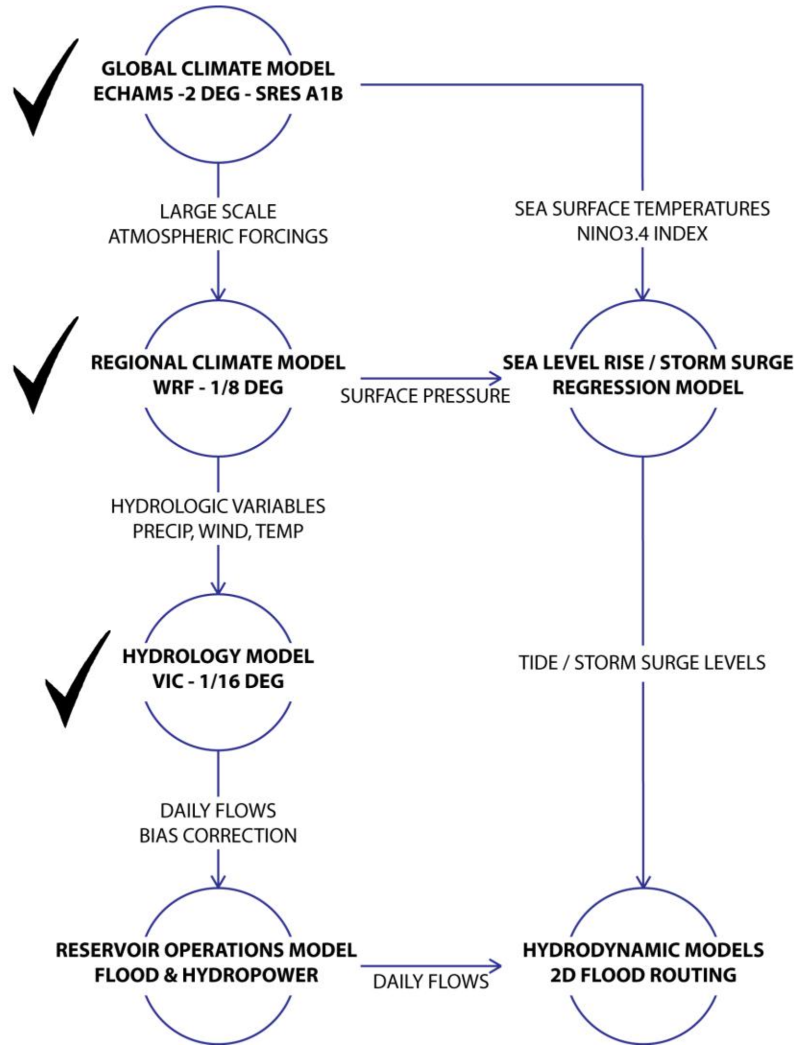
# UNREGULATED HYDROLOGY



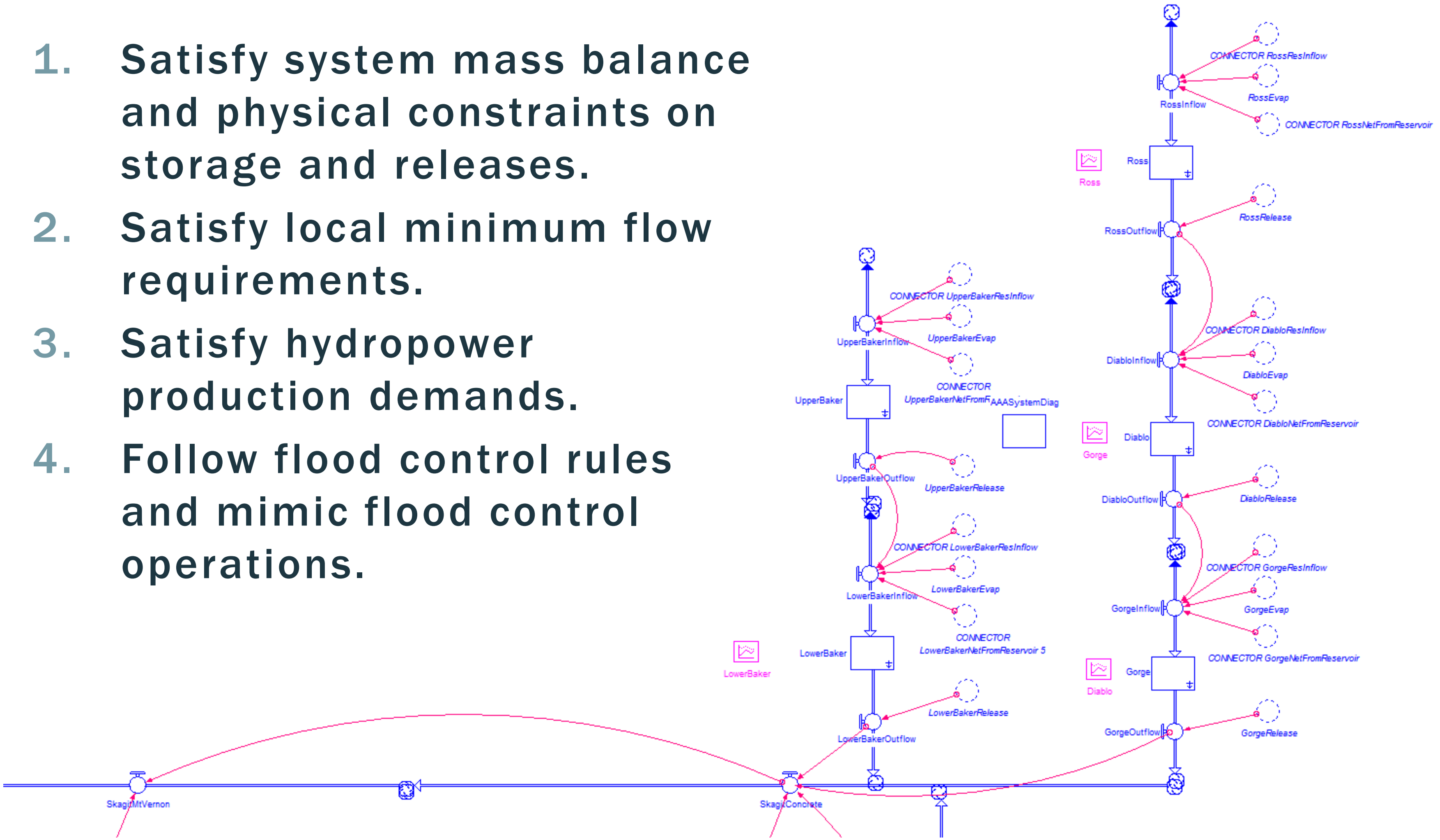
# GETTING FROM THE GCMS TO INUNDATION MAPS

- Ultimately, we're trying to get inundation maps from GCM data
- So far we've got
  - Downscaled atmospheric forcings from climate models
  - Unregulated streamflow projections



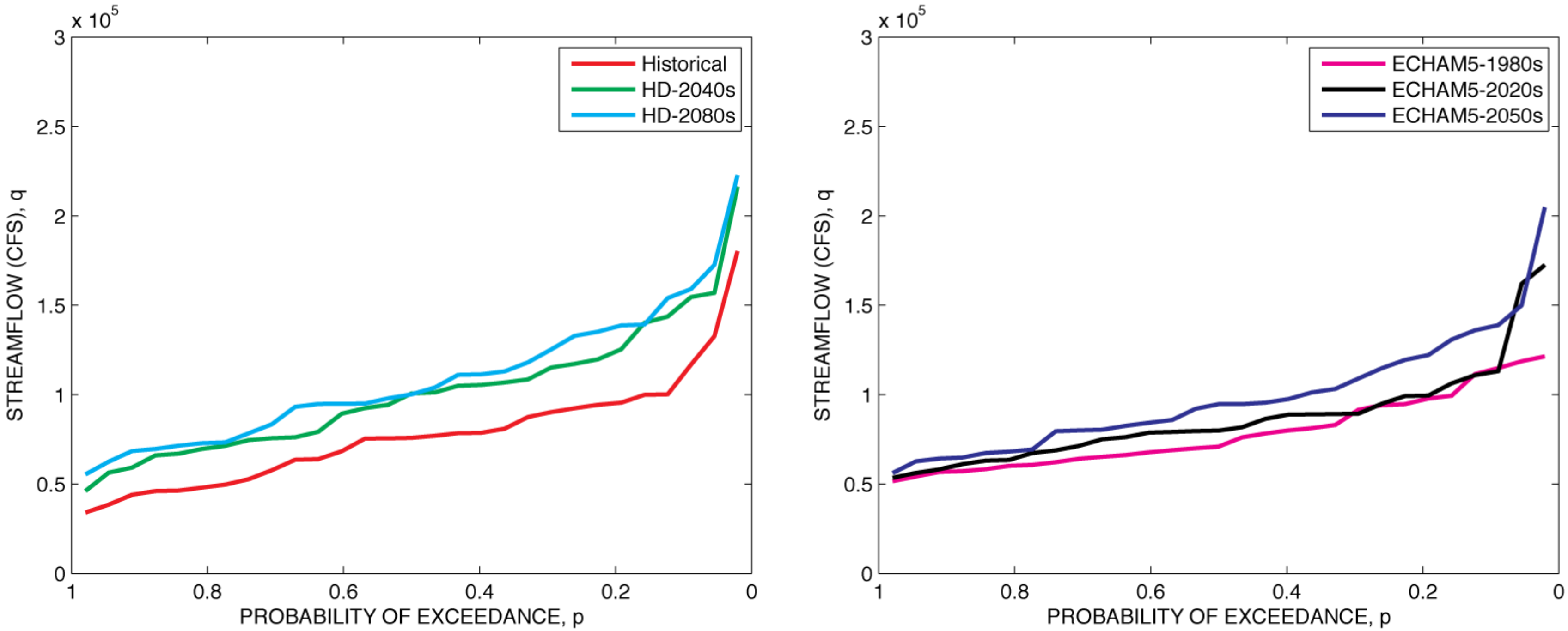
# RESERVOIR MODELING

1. Satisfy system mass balance and physical constraints on storage and releases.
2. Satisfy local minimum flow requirements.
3. Satisfy hydropower production demands.
4. Follow flood control rules and mimic flood control operations.



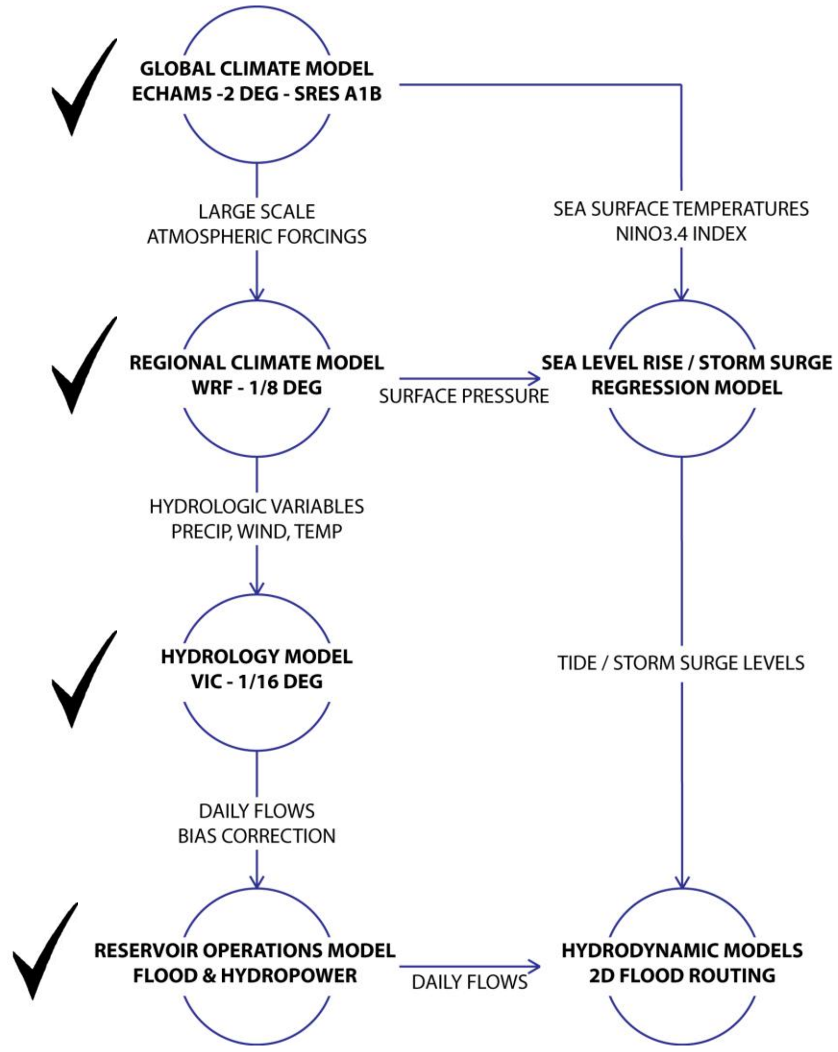
# REGULATED PEAK FLOWS

Skagit River at Mt. Vernon, WA



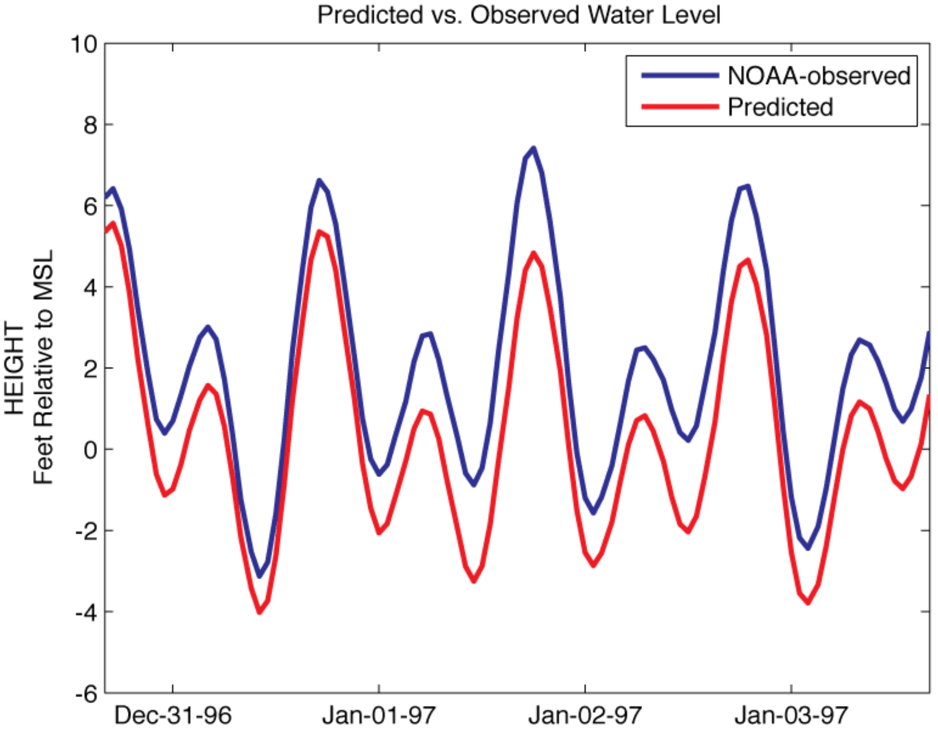
# GETTING FROM THE GCMS TO INUNDATION MAPS

- Ultimately, we're trying to get inundation maps from GCM data
- So far we have:
  - Downscaled atmospheric forcings from climate models
  - Unregulated streamflow projections
  - Regulated streamflow projections

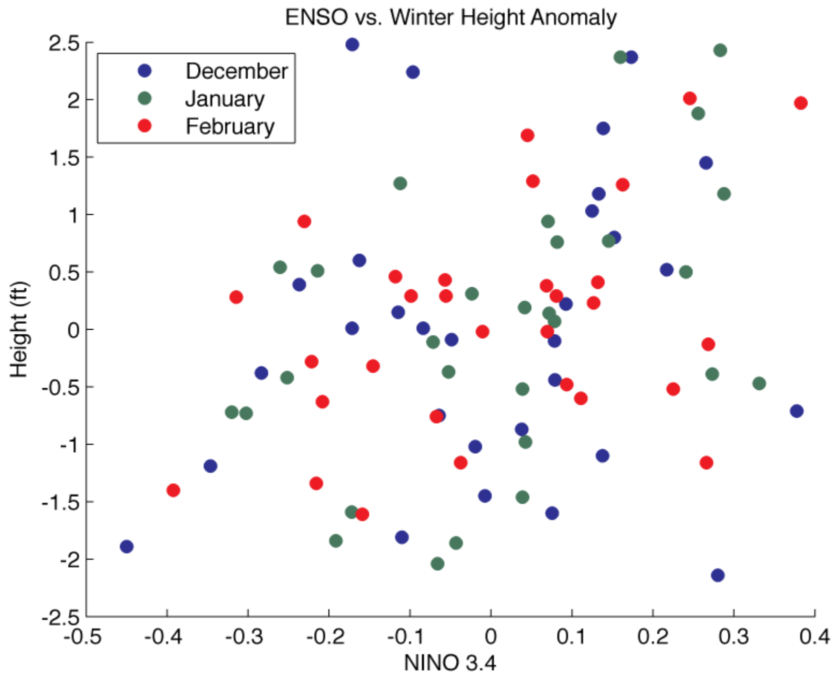


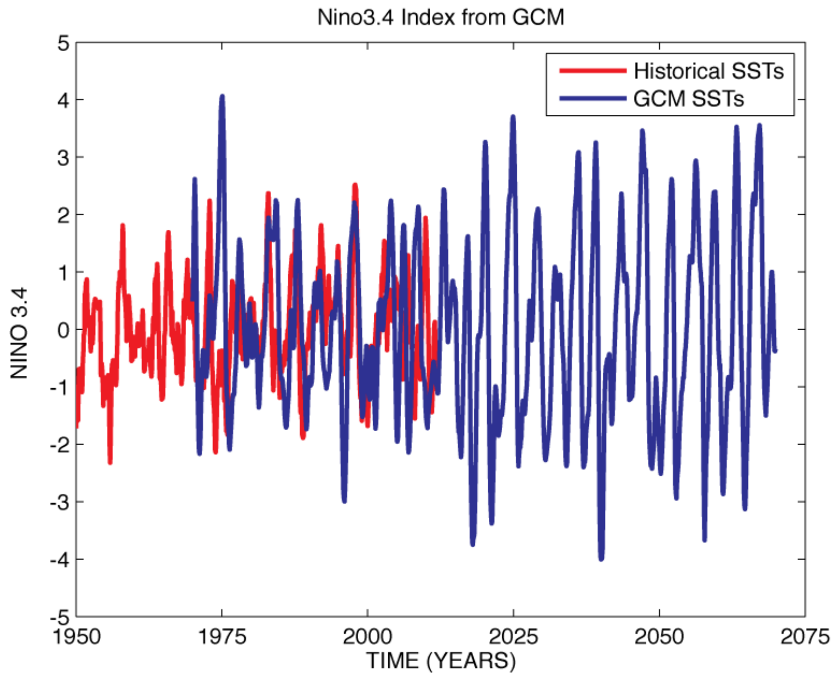
# STORM SURGE
# LINEAR REGRESSION APPROACH

1. **Calculate anomalies and sort by month**
2. **Anomaly = f (Pressure, Pressure Patterns, ENSO)**
   - **Training Data: WRF-Reanalysis, observed ENSO**
   - **Forecast Data: WRF-ECHAM5 and ECHAM5 SSTs**
3. **Add forecasted anomalies and SLR to hourly tide projections**



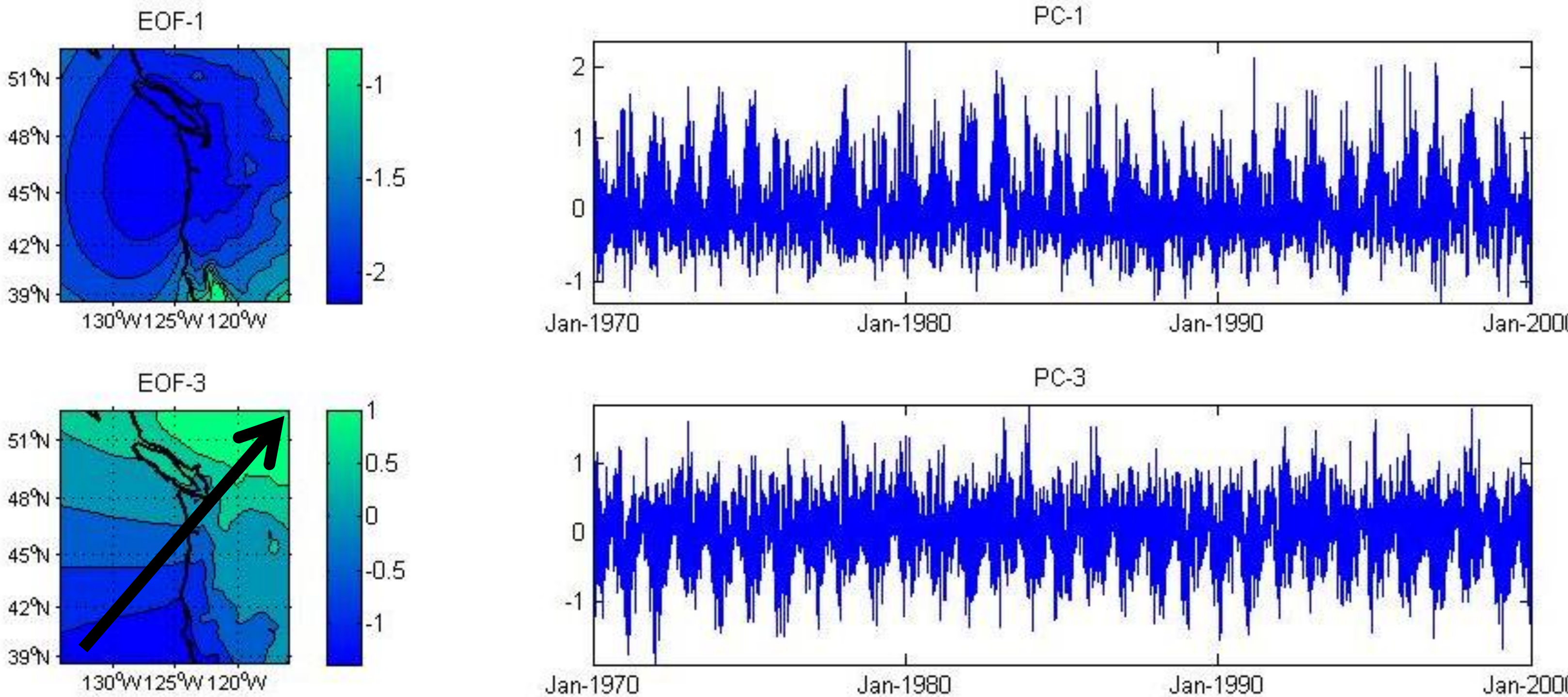
# STORM SURGE
# EL NINO SOUTHERN OSCILLATION



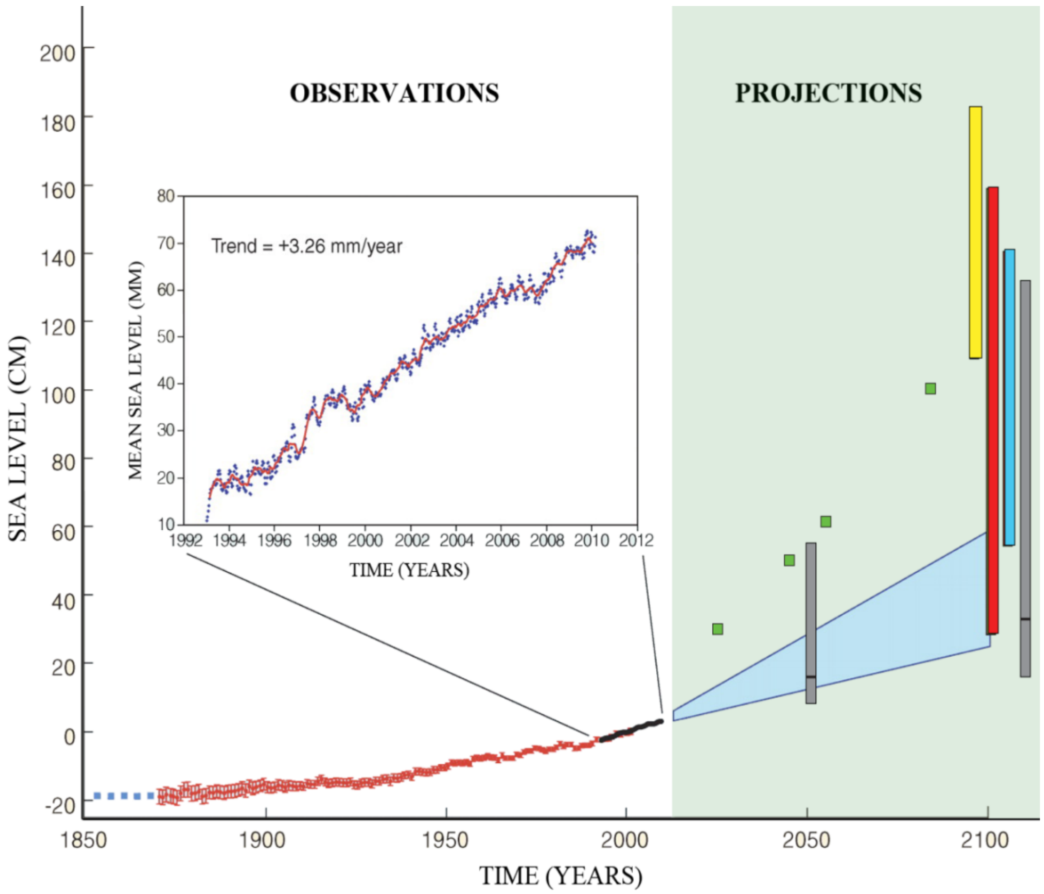

- Linear relationship between ENSO and Winter height anomaly
- Extracted Nino3.4 from GCM SSTs

# STORM SURGE PRESSURE PATTERNS



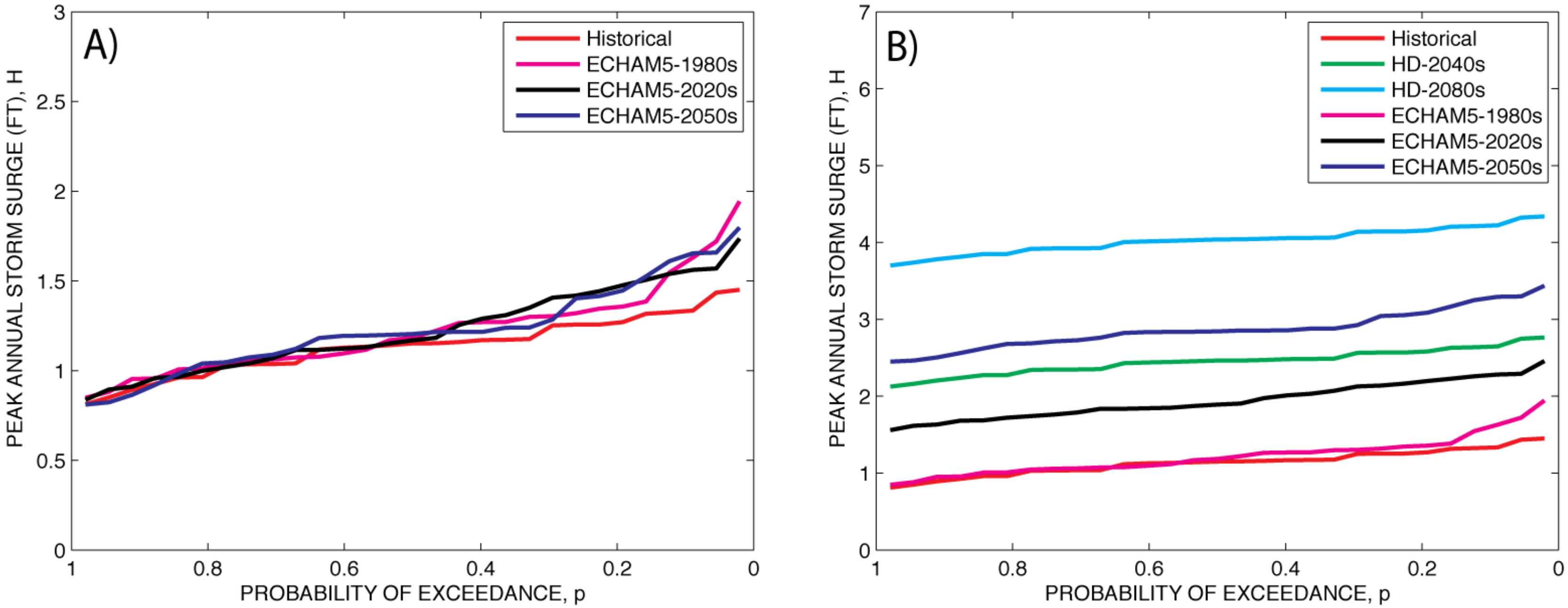

- Used singular value decomposition (SVD) to isolate important regional pressure patterns
- These time series represent the key modes of pressure variability that explain storm surge anomalies

# SEA LEVEL RISE




- Large range in SLR projections
- We used upper end of Mote et al., 2008 projections as a mid-high estimate

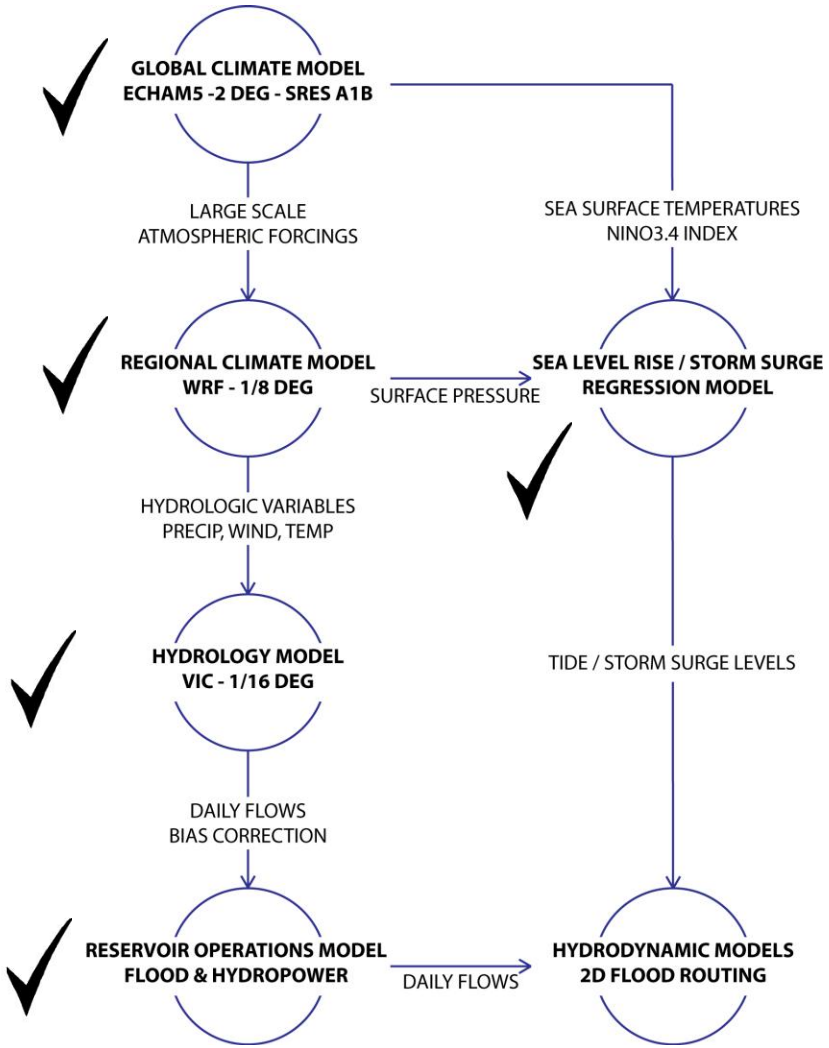
# STORM SURGE AND SLR




- Little to no change in the CDFs between RCM time periods
- SLR, by comparison, drastically changes the CDFs by shifting them all upward

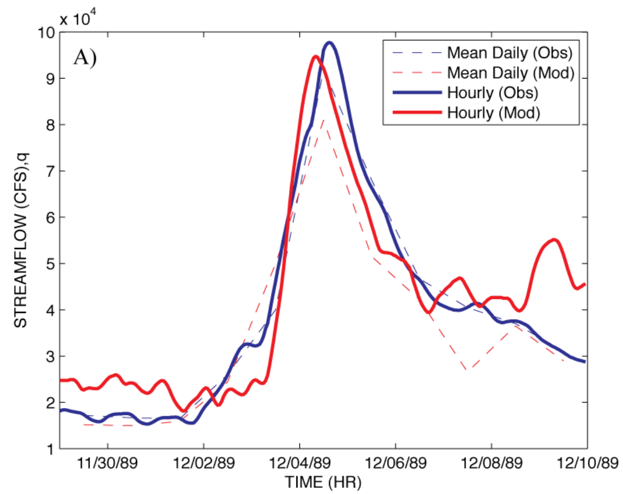
# GETTING FROM THE GCMS TO INUNDATION MAPS

- Ultimately, we're trying to get inundation maps from GCM data
- So far we have:
  - Downscaled atmospheric forcings from climate models
  - Unregulated streamflow projections
  - Regulated streamflow projections
  - Hourly tide and storm surge projections

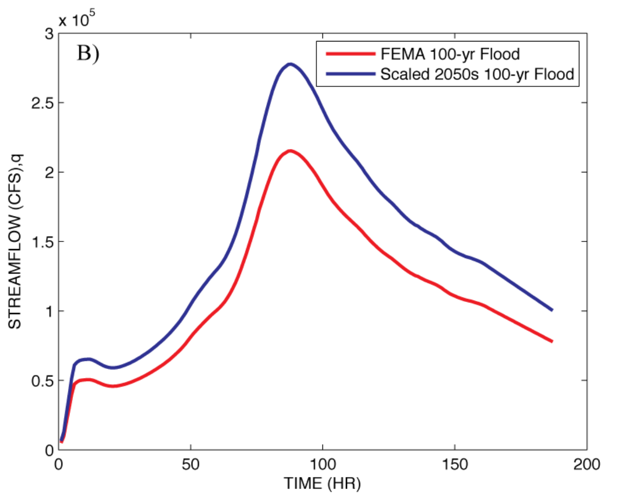


# HOURLY DISAGGREGATION

- WRF storms
  - **Goal**: Assess dynamics of flooding under completely different conditions (storm surge, SLR, hydrograph)
  - ***Approach***: *Steepness Index Unit Volume Flood Hydrograph Approach for Sub-Daily Flow Disaggregation*

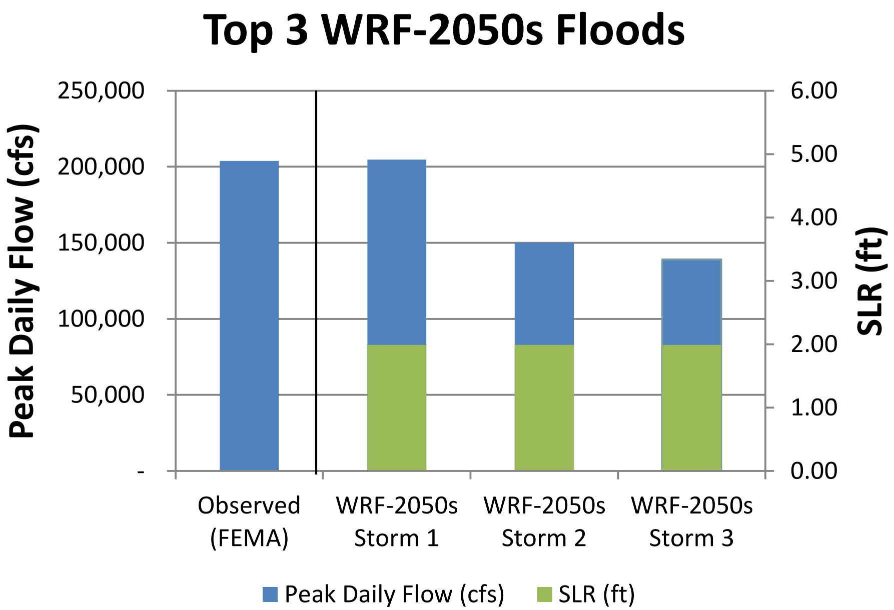


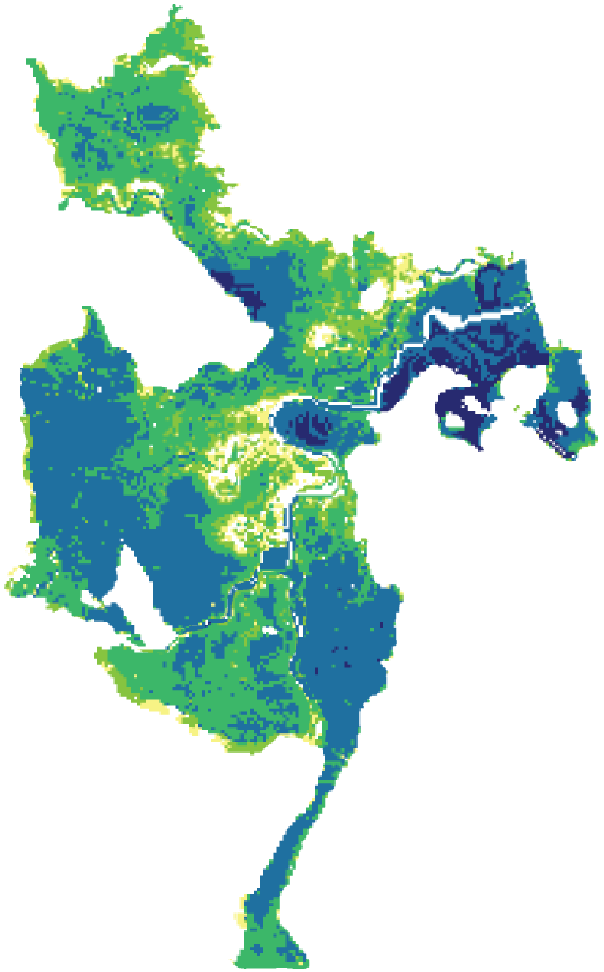

- Scaled FEMA storms
  - **Goal**: Compare flood extents and depths between different time periods (e.g. Historical and 2050s)
  - ***Approach***: Scale by relative increase in 100-yr flood based on GEVD fit to each 30-yr time period



# HYDRODYNAMIC MODELING

- Skagit Model developed by USACE and FEMA
- 2D hydrodynamic model, Flo2D
- Simulates channel and overbank flow in lower Skagit River Basin
- Includes current levees and dikes



# WHAT WE KNEW

- Climate change is expected to increase flood magnitudes, especially in transient mixed rain-snow basins.
  - 100-yr unregulated floods in Skagit and Nisqually Rivers could increase upwards of 50% by the 2080s.
- Sea Level Rise will increase base sea levels.
  - Projections range from 20 to 200 cm by 2100.

# WHAT WE KNOW NOW

- Future storm surge, brought on by barometric and wind effects, is not expected to change significantly.
- Sea level rise is expected to influence extreme water levels much more than changes in storm surge.
- Inundation from flooding in the Skagit is expected to increase by up to 72% by the 2050s given combined SLR and increased flood magnitudes.
- Average depth in 100-yr flood map increases by 10 inches when 2050s flood and SLR are included.
- Using a scenario based approach is an effective way to understand changes in flood magnitudes over time.

# FUTURE WORK

- Hydrodynamic modeling in Nisqually River.
- Investigate FEMA model domain size.
- The uncertainty in SLR estimates is a problem.
- More realizations of GCM/RCM/Hydrology models are necessary to find clear consensus in changes.
- ENSO relationship to flooding.  Teleconnection may not be present in GCMs.
- Bias in absolute value of flooding is a problem for inundation mapping.

# WRF-2050S FLOOD 1
# ALL LEVEES INTACT

**Peak Daily Flow, cfs**

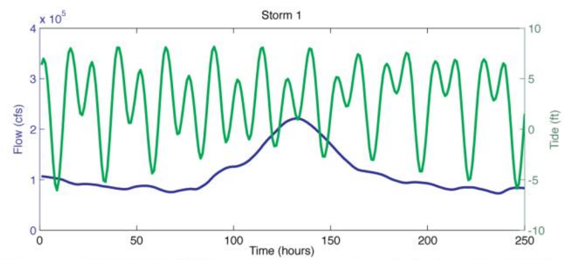
204,718

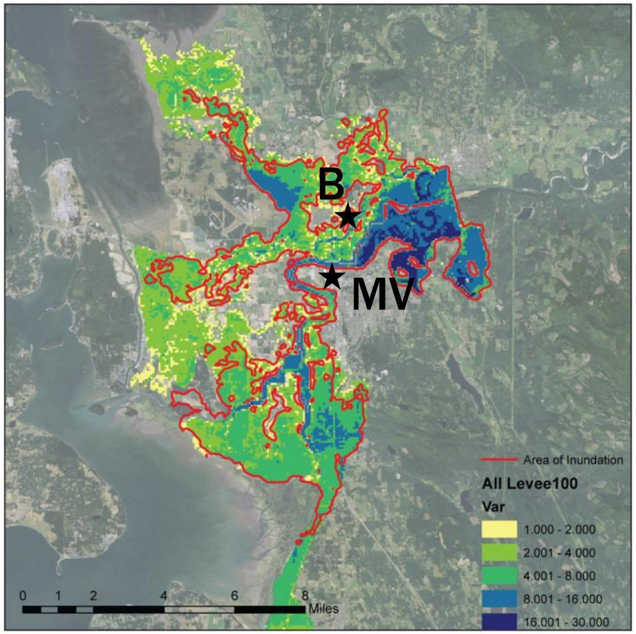
**Sea Level Rise, ft**

1.99

**Storm Surge, ft**

0.90




**1/30/2069**

**Inundation, acres (Relative to 100yrFEMA)**

60,544
(1.43)

**Mt. Vernon Depth, ft**

0.00

**Burlington Depth, ft**

1.58

# WRF-2050S FLOOD 2
# ALL LEVEES INTACT

**Peak Daily Flow, cfs**

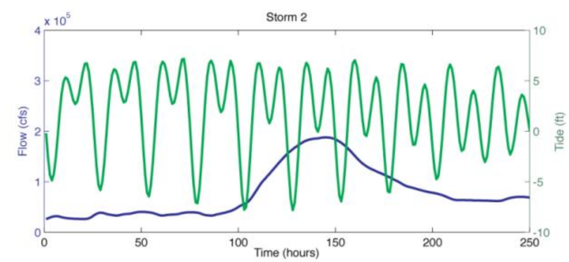
149,890

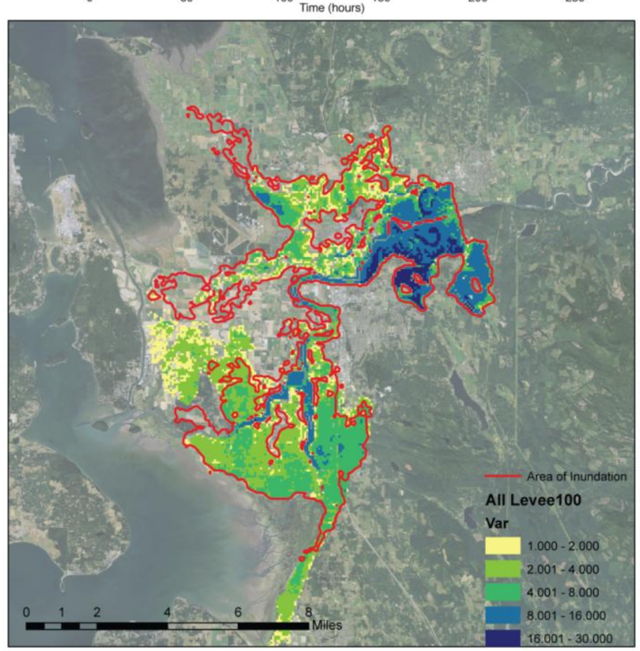
**Sea Level Rise, ft**

1.99

**Storm Surge, ft**

-0.59




**2/4/2053**

**Inundation, acres (Relative to 100yrFEMA)**

43,052
(1.02)

**Mt. Vernon Depth, ft**

0.00

**Burlington Depth, ft**

0.00

# WRF-2050S FLOOD 3
# ALL LEVEES INTACT

**Peak Daily Flow, cfs**

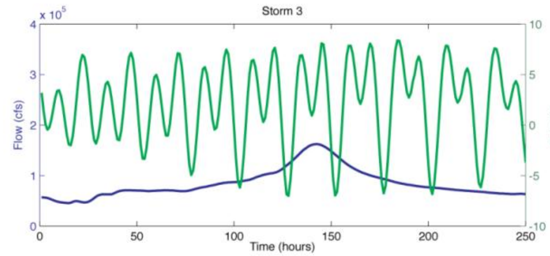
138,945

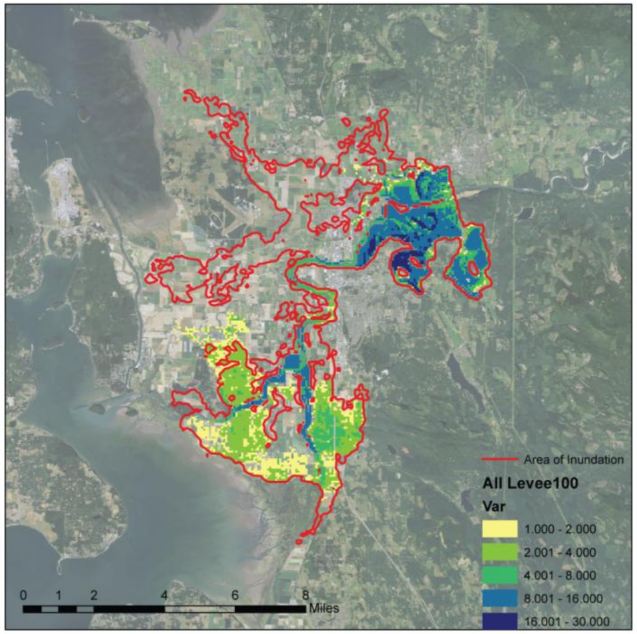
**Sea Level Rise, ft**

1.99

**Storm Surge, ft**

0.31




**11/18/2047**

**Inundation, acres (Relative to 100yrFEMA)**

22,527
(0.53)

**Mt. Vernon Depth, ft**

0.00

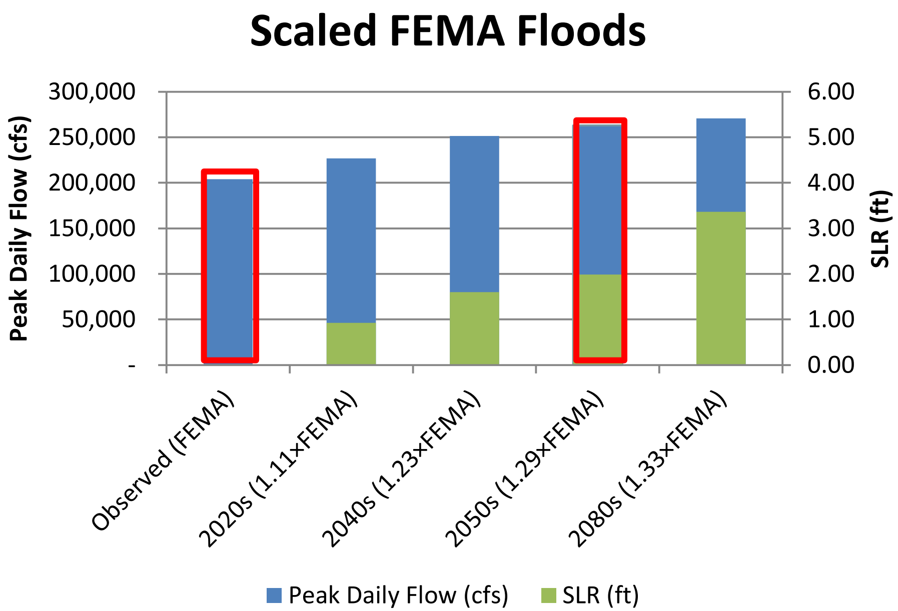
**Burlington Depth, ft**

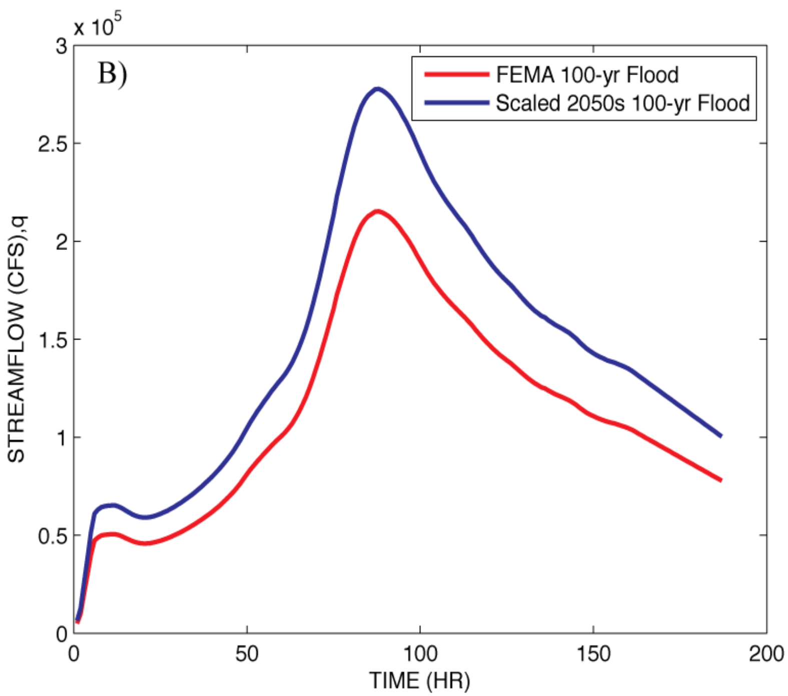
0.00

# 100 YEAR FLOOD MAPPING

- Applied relative changes in 100-year flood to FEMA hydrograph
- Eliminates model bias in peak flows
- Performed composite flood mapping for 2050s (7 levee failure scenarios)

$$FEMA_{2050s} = FEMA \times \frac{100yrWRF_{2050s}}{100yrWRF_{1980s}}$$



# FEMA 100-YEAR FLOOD
# ALL LEVEES INTACT

**Peak Daily Flow, cfs**

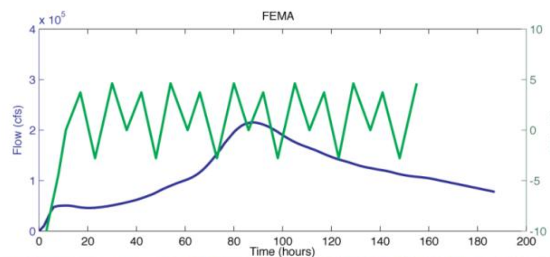
203,835

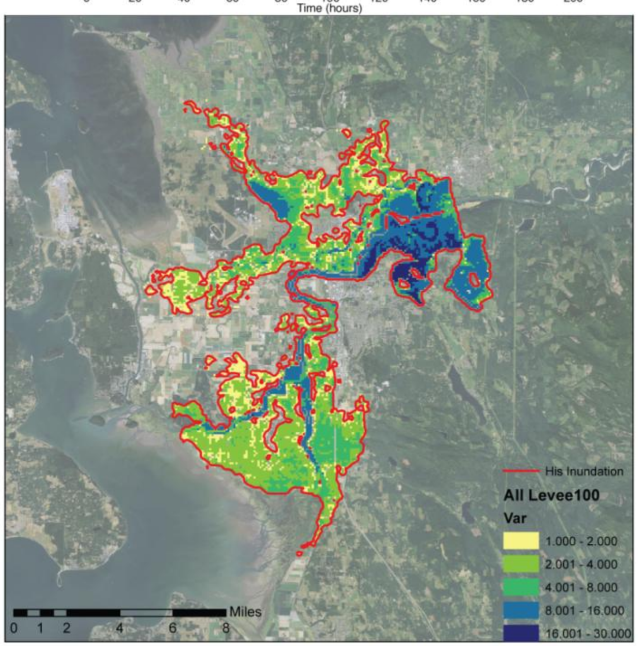
**Sea Level Rise, ft**

0.00

**Storm Surge, ft**

1.5




**FEMA - His**

**Inundation, acres (Relative to His)**

42,266
(1.00)

**Mt. Vernon Depth, ft**

0.00

**Burlington Depth, ft**

0.77

# 2020S 100-YEAR FLOOD
# ALL LEVEES INTACT

**Peak Daily Flow, cfs**

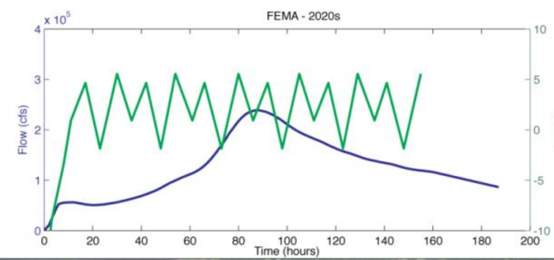
226,697

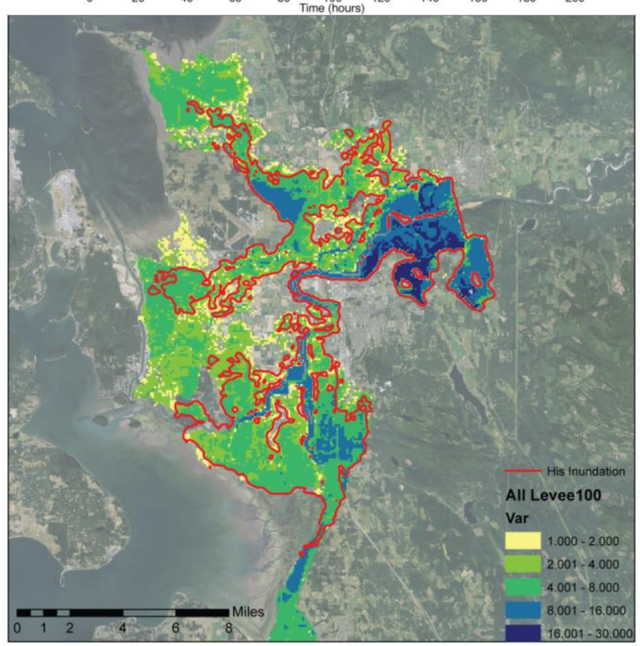
**Sea Level Rise, ft**

0.93

**Storm Surge, ft**

1.5




**FEMA – 2020s**

**Inundation, acres (Relative to His)**

64,878
(1.53)

**Mt. Vernon Depth, ft**

0.00

**Burlington Depth, ft**

1.89

# 2040S 100-YEAR FLOOD
# ALL LEVEES INTACT

**Peak Daily Flow, cfs**

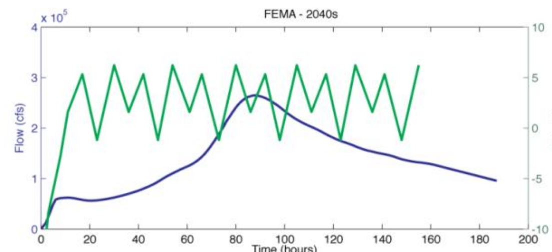
251,441

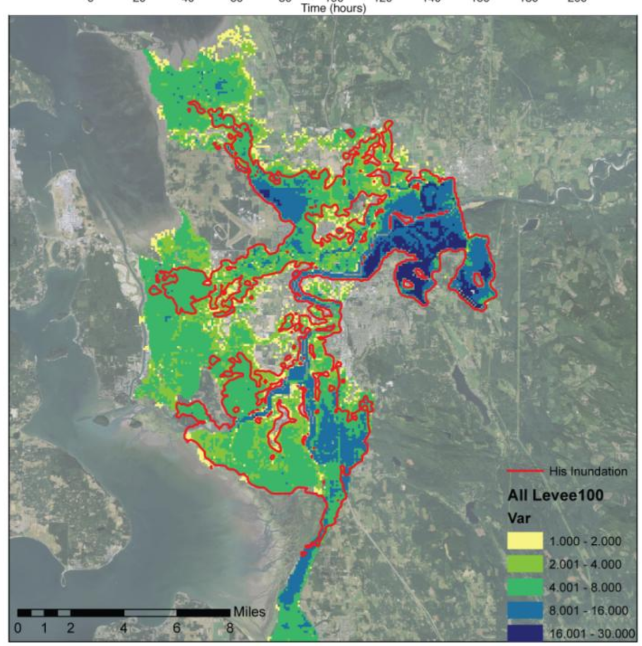
**Sea Level Rise, ft**

1.60

**Storm Surge, ft**

1.5




**FEMA – 2040s**

**Inundation, acres (Relative to His)**

71,236
(1.69)

**Mt. Vernon Depth, ft**

0.45

**Burlington Depth, ft**

2.40

# 2050S 100-YEAR FLOOD
# ALL LEVEES INTACT

**Peak Daily Flow, cfs**

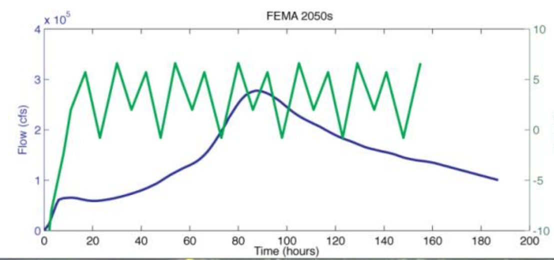
263,016

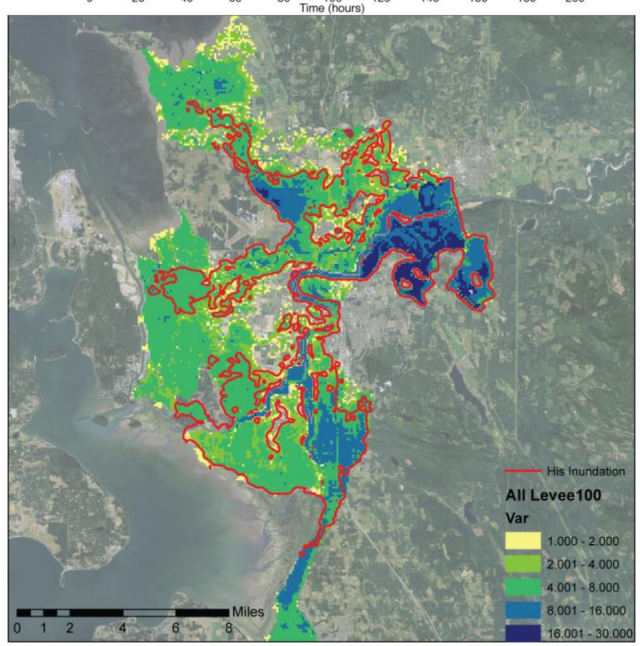
**Sea Level Rise, ft**

1.99

**Storm Surge, ft**

1.5




**FEMA – 2050s**

**Inundation, acres (Relative to His)**

72,555
(1.72)

**Mt. Vernon Depth, ft**

0.89

**Burlington Depth, ft**

2.55

# 2080S 100-YEAR FLOOD
# ALL LEVEES INTACT

**Peak Daily Flow, cfs**

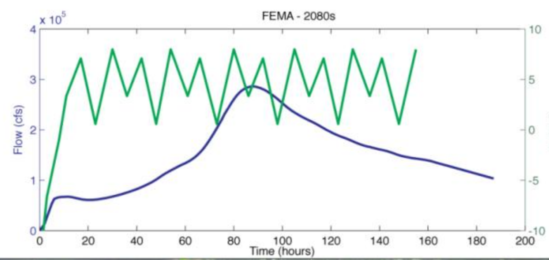
270,803

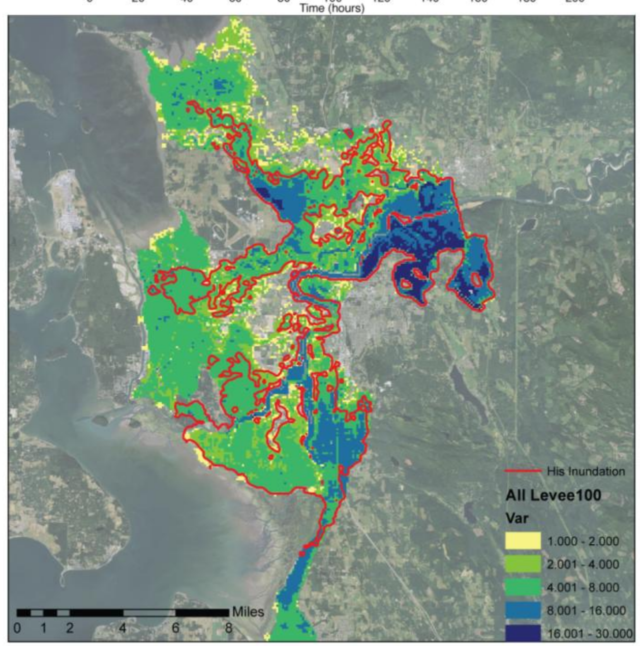
**Sea Level Rise, ft**

3.36

**Storm Surge, ft**

1.5




**FEMA – 2080s**

**Inundation, acres (Relative to His)**

73,914
(1.75)

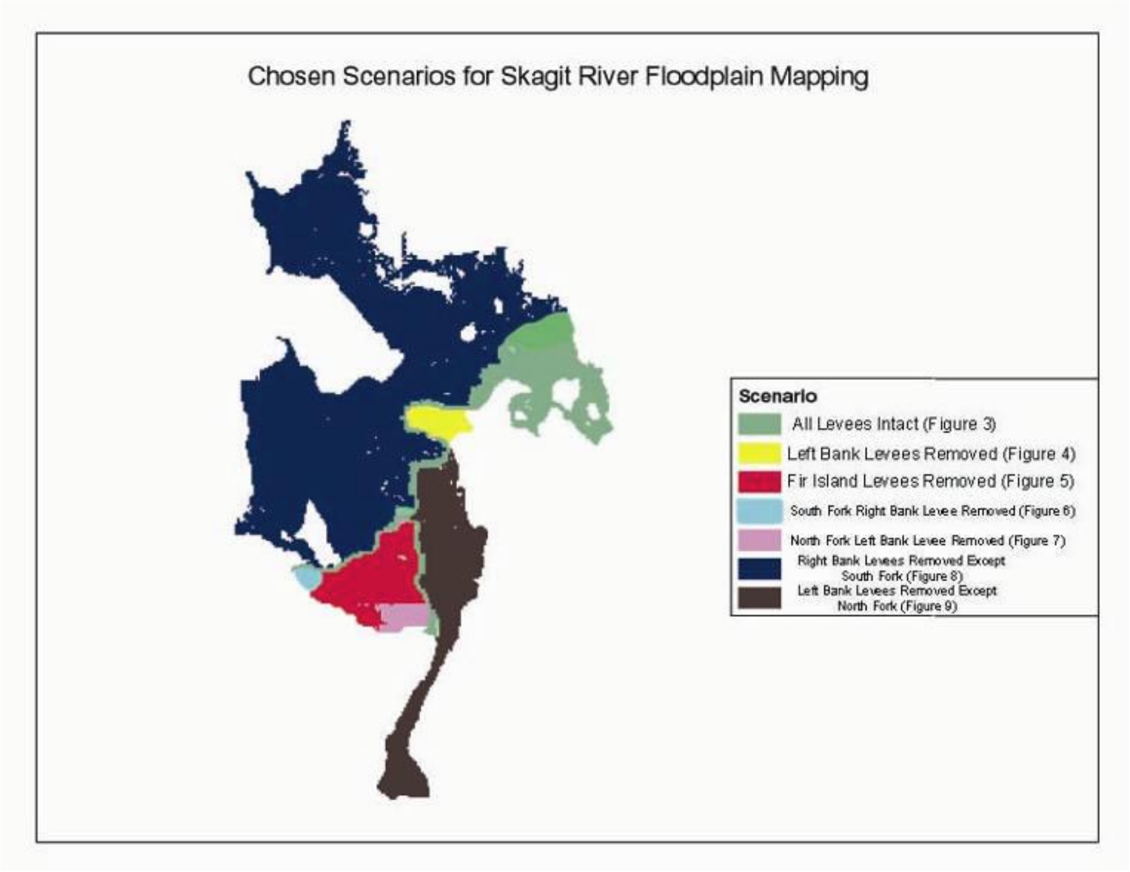
**Mt. Vernon Depth, ft**

0.98

**Burlington Depth, ft**

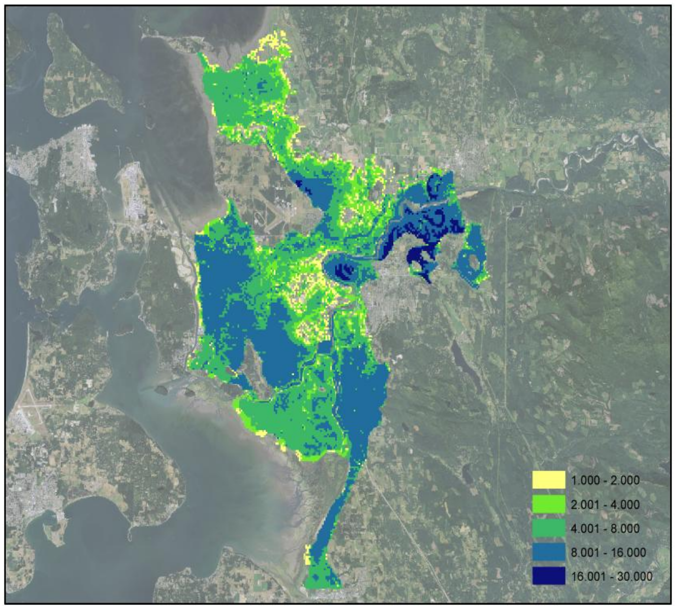
2.72

# COMPOSITE FLOOD MAPS
# 7 LEVEE FAILURE SCENARIOS



# COMPOSITE FLOOD MAPS
# 7 LEVEE FAILURE SCENARIOS

FEMA Composite Map



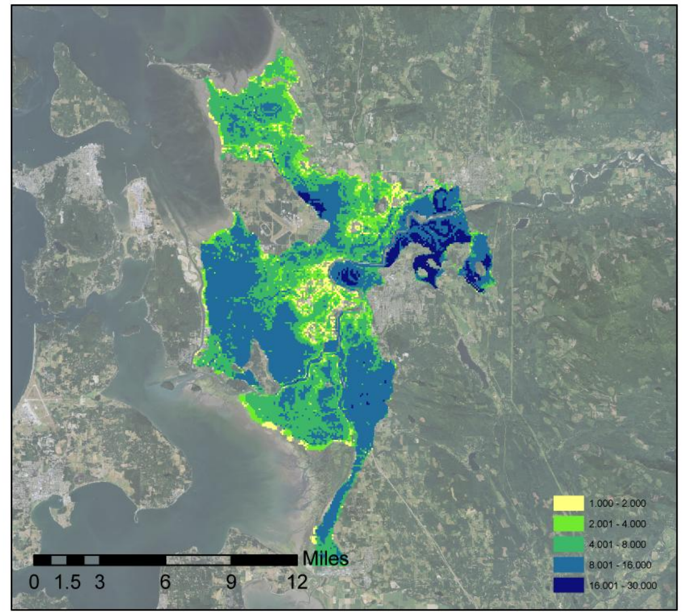

**Mt. Vernon Depth, ft**

**11.31**

**Burlington Depth, ft**

**2.79**

2050s Composite Map




**Mt. Vernon Depth, ft**

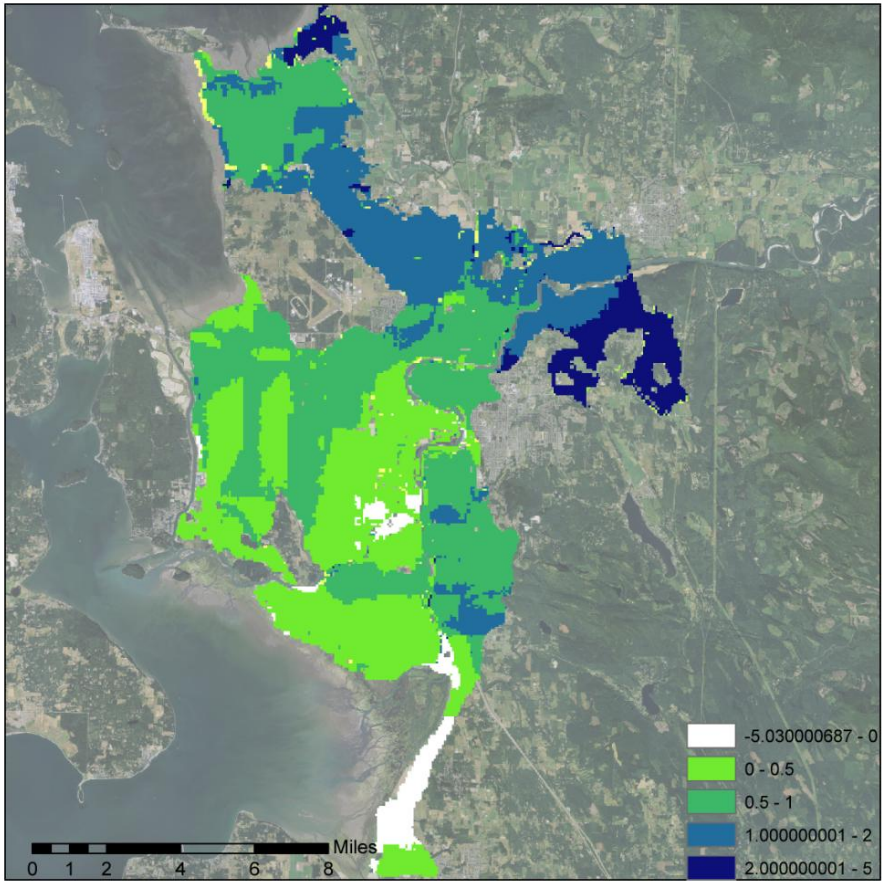
**12.02**

**Burlington Depth, ft**

**3.70**

# DIFFERENCE BETWEEN COMPOSITE FLOOD MAPS

(2050s Composite Map – FEMA Composite Map)




**Mt. Vernon Depth, ft**

0.71

**Burlington Depth, ft**

0.91