# A System View of Water Level Processes in the Lower Columbia River

David Jay
Department of Civil & Environmental Engineering
Portland State University, Portland, OR

Amy Borde and Heida Diefenderfer
Pacific Northwest National Laboratory, Marine Sciences Laboratory
Sequim, WA

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# Roadmap –

- Methods
- Phenomenology: how do tides evolve along-channel and in wetlands in a complex, heavily altered system?
- Processes: what factors dominate water level variations and inundation along the tidal-fluvial continuum:
- How do wetland water level phenomena and processes differ from those in channels?
- Applications:
  - Hindcasting/forecasting inundation in wetlands and channels
  - Vegetation analyses via sum exceedance values SEV
  - CR system zonation based on physical processes
  - Future MSL rise, climate change and human alterations
- This presentation is based on:

Jay, D. A., K. Leffler, H. L. Diefenderfer, and A. B. Borde, in press 2014, Tidal-fluvial and estuarine processes in the Lower Columbia River: I: along-channel water level variations, Pacific Ocean to Bonneville Dam, *Estuaries and Coasts*.

Jay, D. A., A. B. Borde, and H. L. Diefenderfer, submitted 2013, Tidal-fluvial and estuarine processes in the Lower Columbia River: II: Water Level Models, Inundation, Reach Classification and Vegetation, *Estuaries and Coasts*.

# Purpose –

- Provide a comprehensive view of water level processes in the wetlands and channels of the LCR
  - Examine water levels in both the time and frequency domains to understand the dominant processes and phenomena
  - Relate water level processes and inundation to vegetation patterns
    - See Amy Borde’s work
  - Consider system zonation in light of water level patterns and hard constraints
  - Provide tools to think about climate change MSL rise, and human alterations

# Analysis Methods for Non-Stationary River Tides –

- Continuous wavelet transform (CWT) methods (Jay and Flinchem 1997):
    - Gives 1 constituent per species; for very non-stationary tides, this appropriate
    - Doesn't provide an understanding of numerous types of tide-flow interactions
- Three new approaches:
    - Physically based regression models of higher high water (HHW), lower low water (LLW), and mean water level (MWL); based on Kukulka and Jay (2003) and this paper
    - Non-stationary harmonic analysis (NS-Tide; Matte et al. 2013, in JAOT)
        - Based on T-Tide and RT_Tide (Pawlowicz et al. 2002; Leffler and Jay, 2009)
        - Incorporates known non-stationary forcing in basis functions
    - Modified CWT (Under development):
        - Can obtain up to 11 constituents per species
- For today: mostly CWT and regression model approaches plus conventional tidal analysis (RT_Tide; Leffler and Jay, 2009)
- Tidal analysis is one of the black arts….

# Methods: Regression Models –

- Determine LLW, MWL and HHW and tidal properties daily (25hr window)
- Determine D1 (diurnal), D2 (semidiurnal) and overtide amplitudes and phases with CWT methods
- Relate LLW, MWL and HHW to external forcing by ocean tides, upwelling (via NOAA CUI), sea level pressure (SLP) and river flow with regression models applied to each station, for 1980s or 1991-2012 records:

$$\mathrm{LLW} = a_{0k} + a_{1k} Q_B^{m_1} + a_{2k} Q_{WR}^{n_1} + a_{3k}\mathrm{CUI} + a_{4k}\left(\frac{T_{R,H}^{s_1}}{(1+Q_B+Q_{WR})^{r_1}}\right)$$

$$\mathrm{HHW} = b_{0k} + b_{1k} Q_B^{m_2} + b_{2k} Q_{WR}^{n_2} + b_{3k}\mathrm{CUI} + b_{4k}\left(\frac{T_{R,H}^{s_2}}{(1+Q_B+Q_{WR})^{r_2}}\right)$$

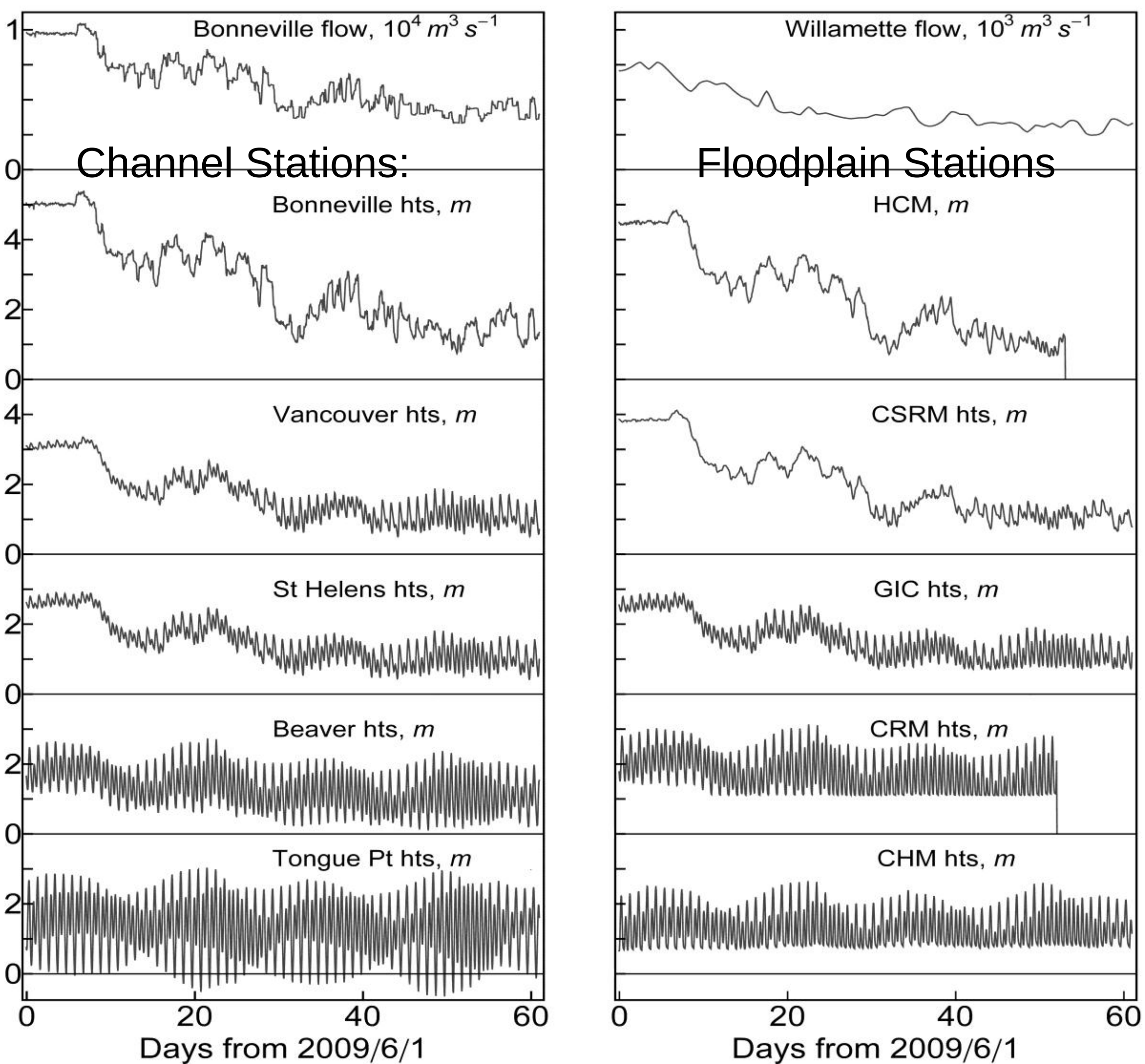
$$\mathrm{MWL} = c_{0k} + c_{1k} Q_B^{m_3} + c_{2k} Q_{WR}^{n_3} + c_{3k}\mathrm{CUI} + c_{4k}\left(\frac{T_{R,H}^{s_3}}{(1+Q_B+Q_{WR})^{r_3}}\right)$$

| | |
|---|---|
| $Q_B$ | = daily mean Columbia flow at Bonneville Dam or Beaver, 1000s of $m^3/s$ |
| $Q_{WR}$ | = daily mean Willamette flow at Portland, 1000s of $m^3/s$ |
| $T_{R,H}$ | = Greater diurnal tidal range (m) at Hammond |
| CUI | = daily Coastal Upwelling Index, in $10m^2s^{-1}$, positive for upwelling |
| $a_{ik}$ to $c_{ik}$, i=0,4 | = regression parameters for each station and model |
| k | = index for stations, k=1,19 |

# How do Tides Evolve Along-Channel?

- Water levels are influenced by annual river flow cycle, SLP variations, upwelling/downwelling, and power peaking (1d and 7d)
- Used multiple tools: power spectra, RT_Tide & CWT
- Wetland tides are different from channel tides due to:
  - Flooring and wave distortion
  - Increased friction
  - Periodic isolation from the river
- Thus, wetland tides are more non-linear and complicated, but less energetic
- We have 35 one to-two year wetland pressure gauge records

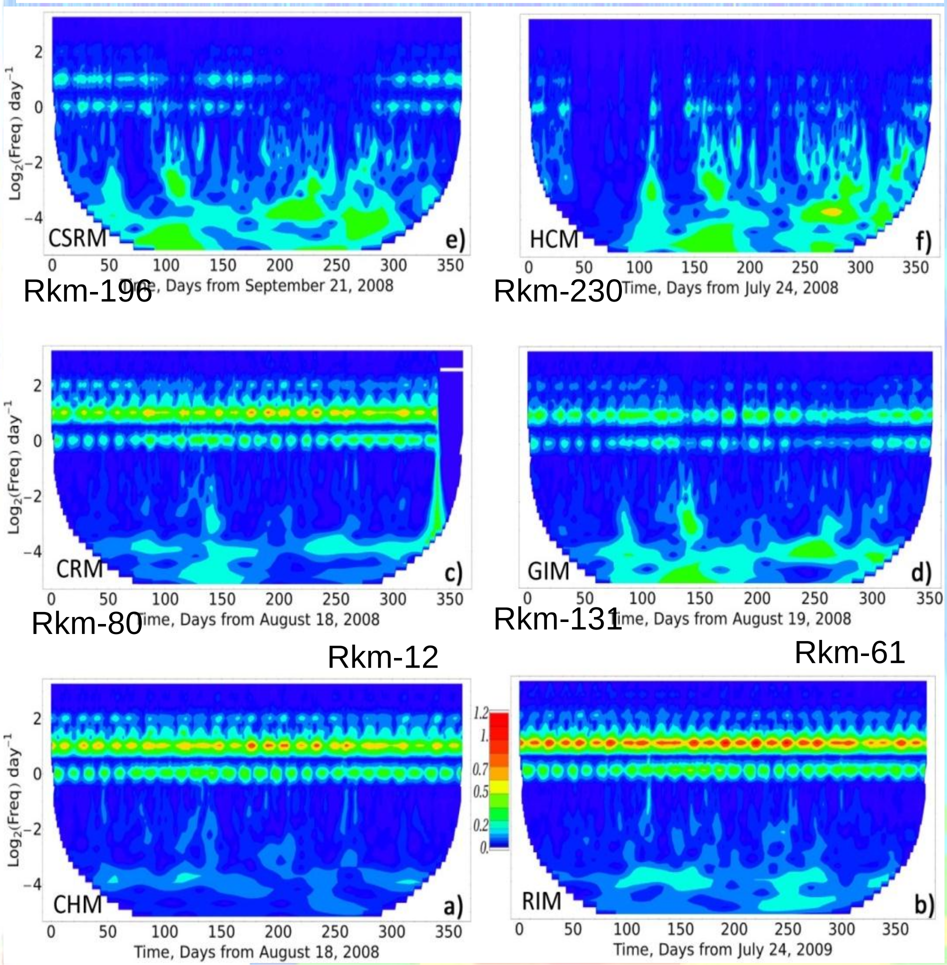
Flows and water levels during the 2009 Freshet:



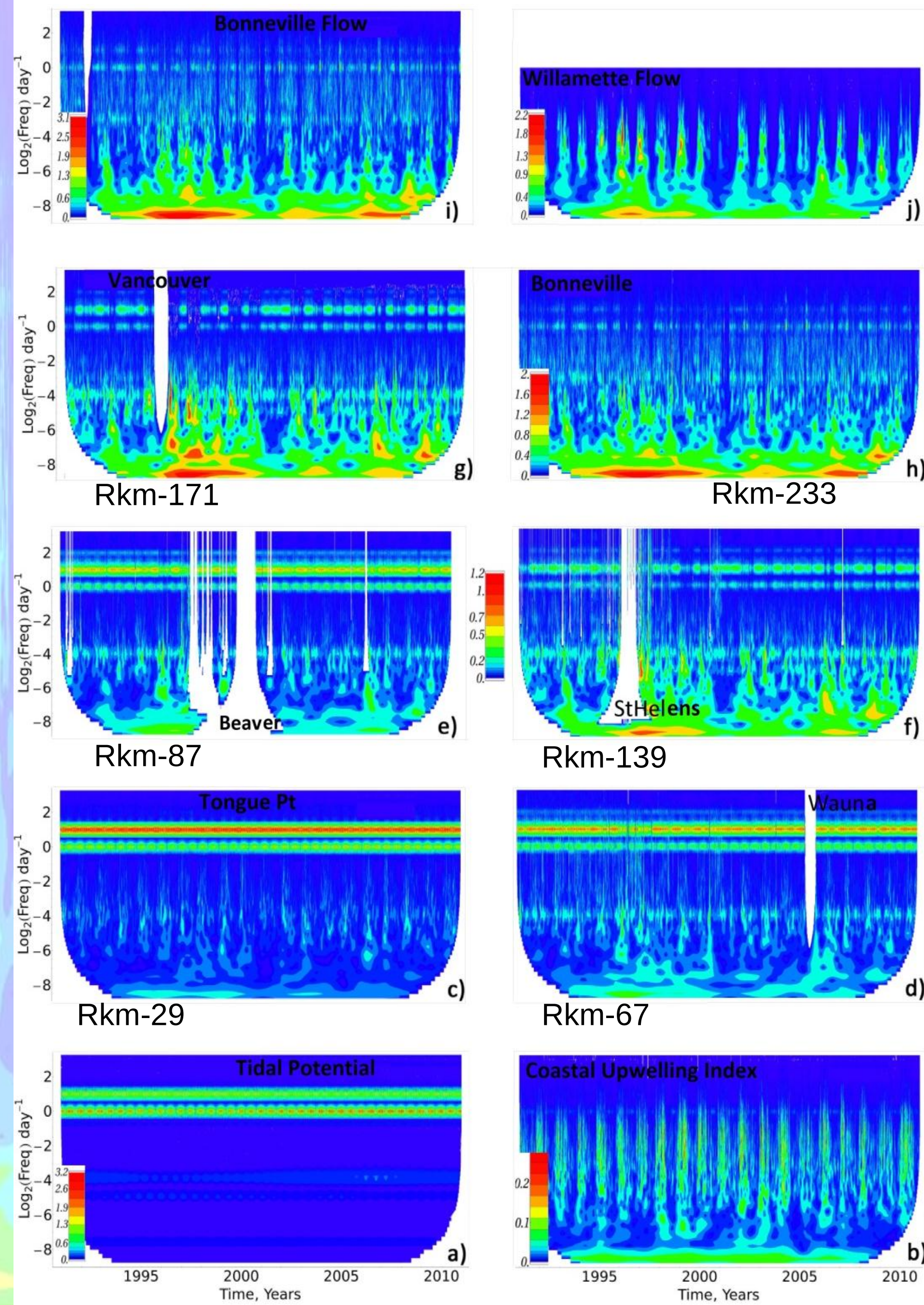
# CWT Scaleograms –

- Note transition from stationary (horizontal bands) to event cones (vertical) upriver
- Estuary stations look like coastal forcing; upriver stations look like fluvial forcing
- Floodplain stations are eccentric!

## Floodplain Stations; 1yr records:




## Channel Stations & Forcing: 1991-2012

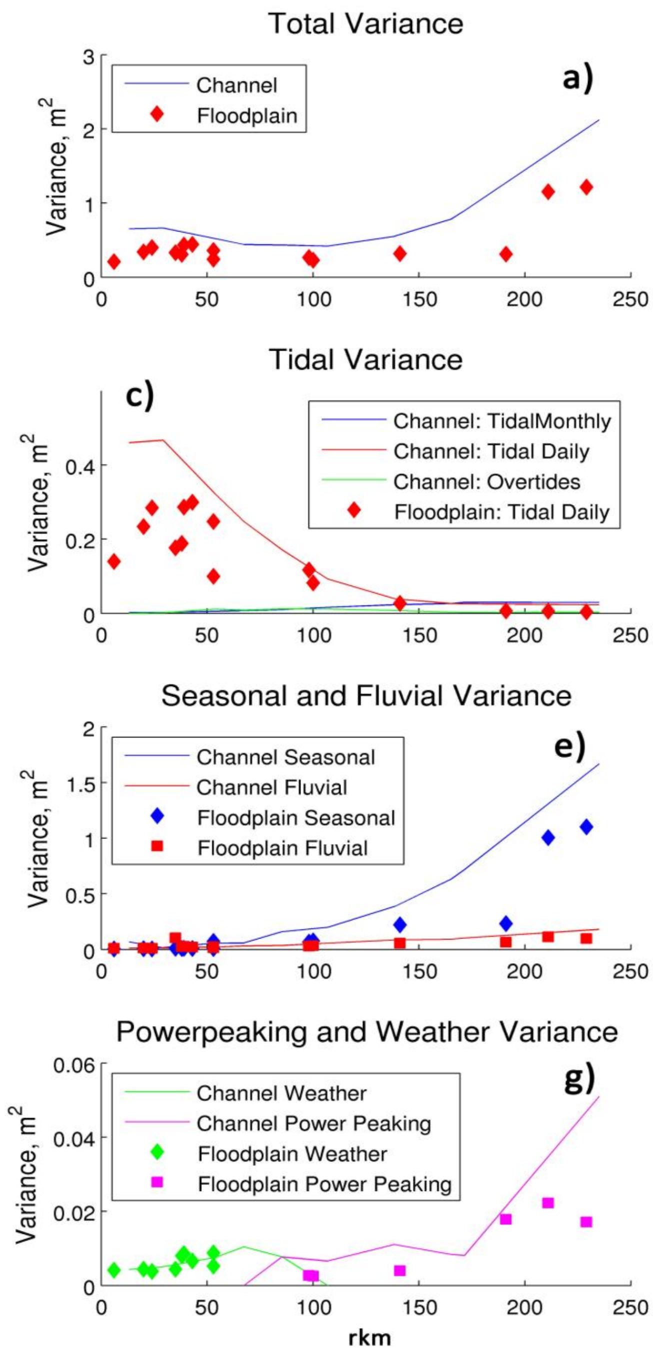


# Variance Analysis Reveals Spatial Patterns –

## What is important where?

- Total variance increases upriver
- Wetlands have less variance
- Tidal variance decreases, fluvial variance increases upriver
- Power peaking is strong above Vancouver, evident from Wauna landward
- Weather variance is hard to detect landward of Longview

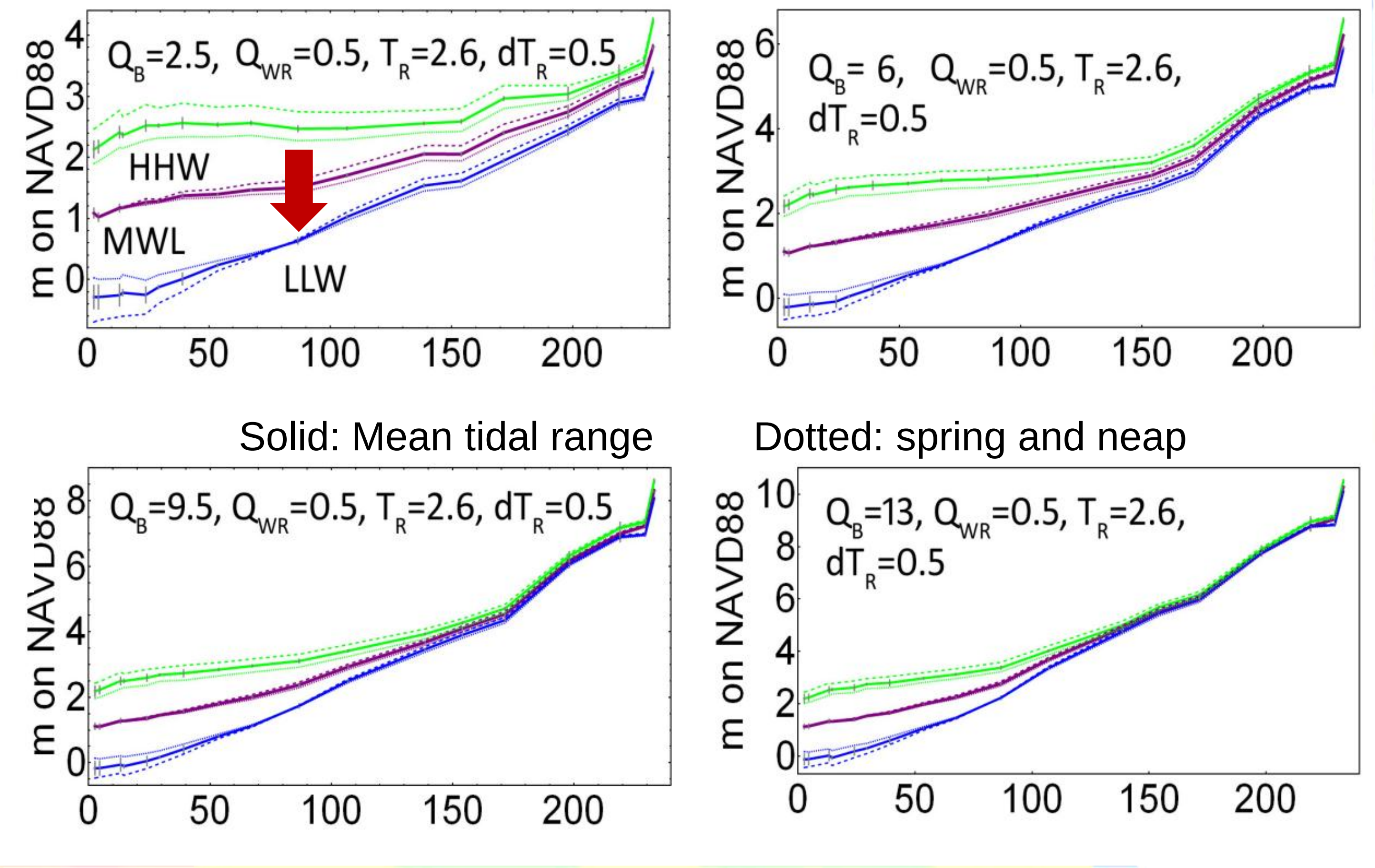
Variance, $m^2$



# Regression Model Results –

- Regression models provide a compact means to summarize system properties
- Note the different neap- spring behavior of MLW above & below Beaver (red arrow)
- Defines the tidal river:
  - Below Beaver, LLW is lower on <u>spring</u> tides
  - Above Beaver, LLW is lower on <u>neap</u> tides
- Increasing flow suppresses tidal monthly variations

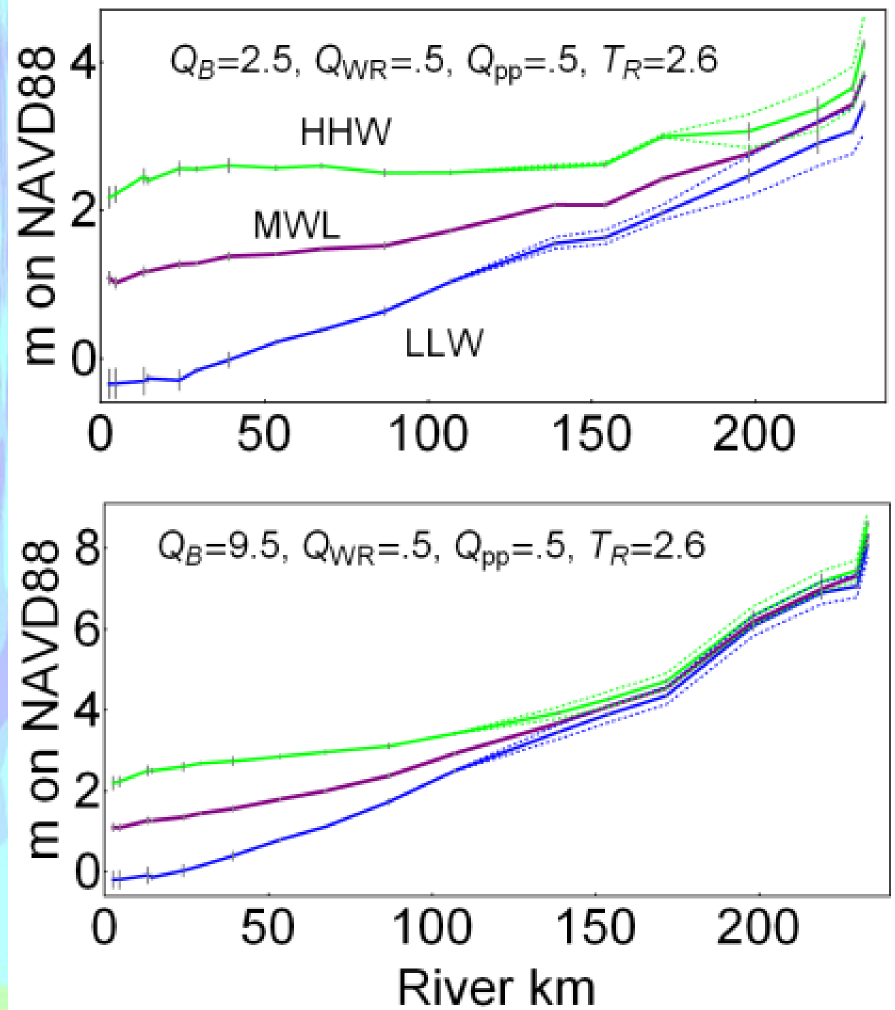
Effects of Flow & tidal range variations



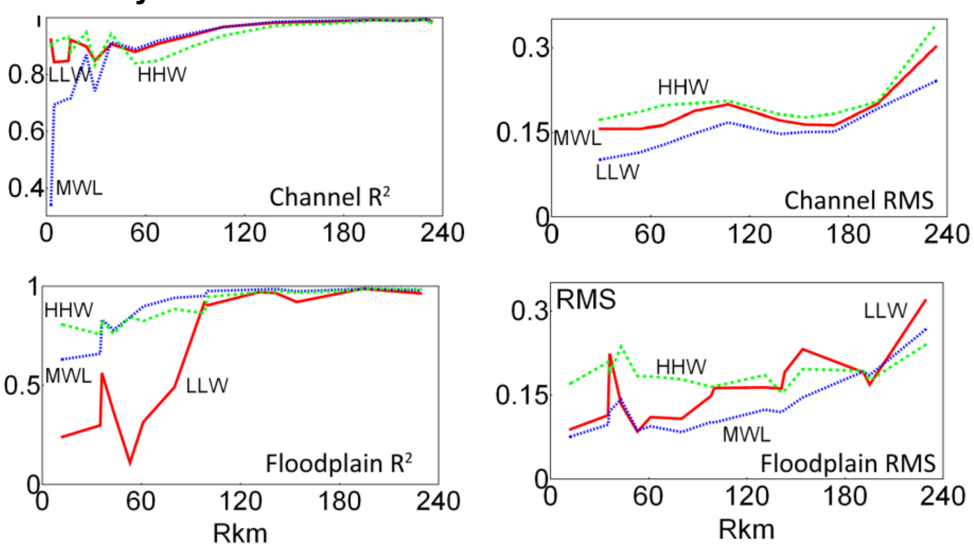
# Regression Model Results (More) –

- Effects of power peaking, ±500m³/s:
  - Power peaking travels as a pseudo-tide downriver
  - Near Bonneville, power peaking controls daily variations
  - Power peaking is less evident during high flow periods – it damps out, like any wave
- Though simple, regression models explain processes well
  - RMS error is ~0.08 to 0.2m except near Bonneville
  - Wetlands are harder to model

Varying CR flow and power peaking:



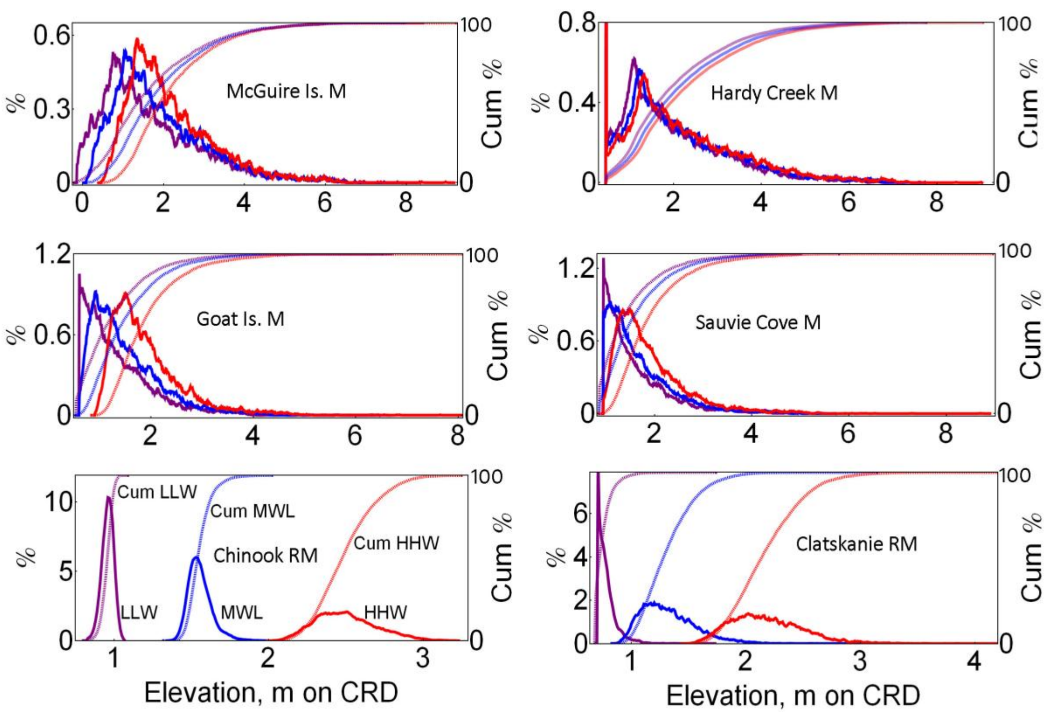

Adjusted $R^2$ and RMS errors



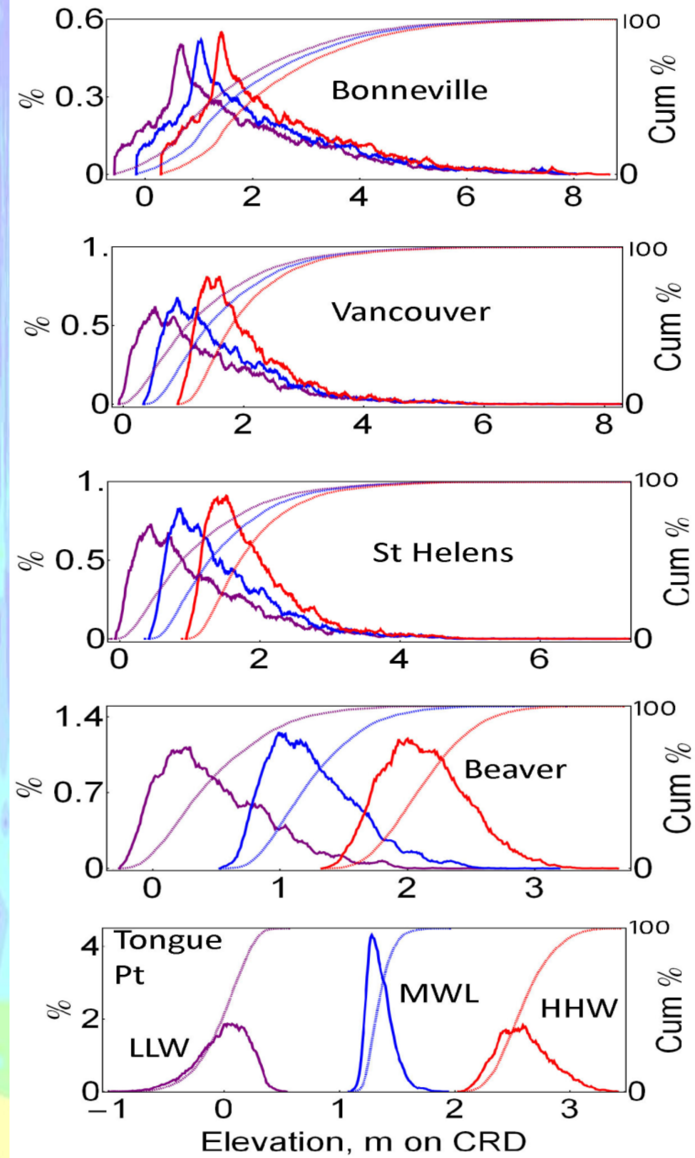
# Application: Inundation Patterns 1991-2011 –

- Regression models were used to hindcast LLW, MWL and HHW for channel and wetland stations
- Skewness varies with parameter & location:
  - Longest tail to right on LLW upriver, left in estuary
- Wetland water levels are severely floored upriver, but also at CRM
  - Hardy Creek is sometimes isolated from the river

Wetland inundation patterns:



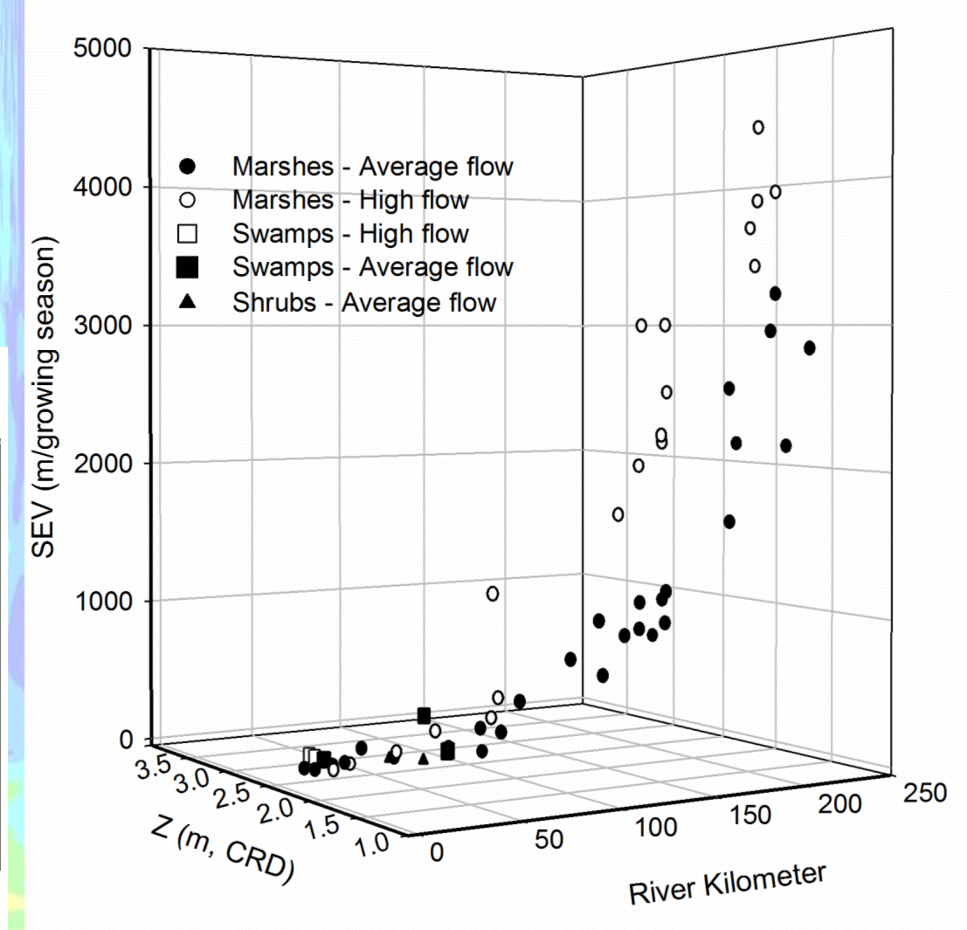

Channel inundation patterns:



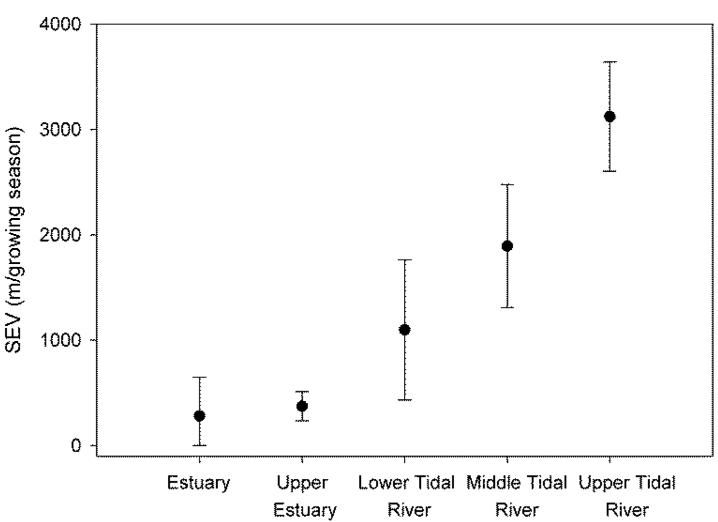
# Application: Predicting Sum Exceedance Values (SEV) –

- SEV connects water levels, flow and vegetation patterns:
  - SEV is the sum of hourly water levels above marsh level during the growing season
  - SEV increases strongly upriver and in wet years
  - Because wetland type varies along channel, SEV varies with wetland type
  - A potential SEV statistic (pSEV) can be calculated from channel tide gauges that accurately models SEV at nearby wetland stations
    - Not necessary to have actual wetland records for a specific year
    - Validation data can be taken from PNNL data set

SEV as a function of Rkm & wetland elevation:



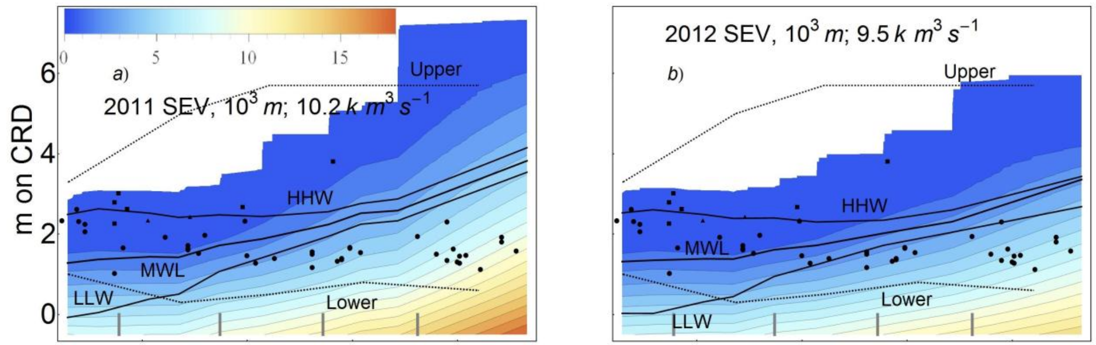

SEV and LCR zones:



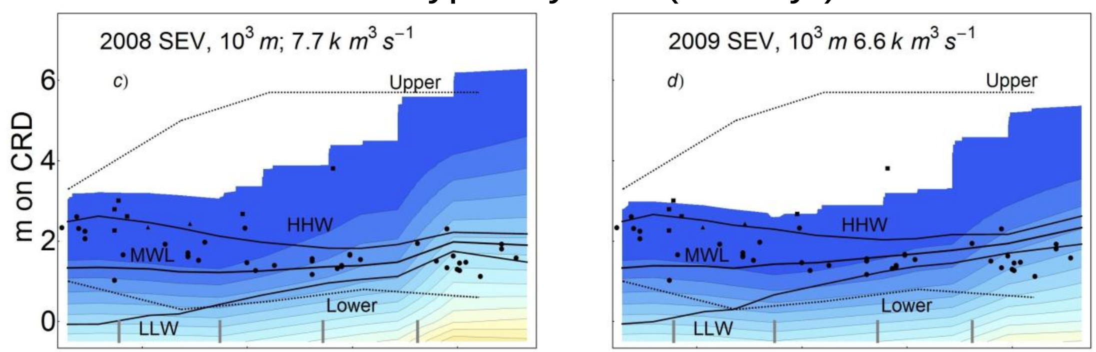
# Application: SEV Values by Year –

- The horizontal axis is Rkm
- The vertical axis is wetland elevation (m)
- The color is SEV in $10^3$m/yr
- Normally, SEV increases strongly with RKM and at low wetland elevations
- Very dry years have more SEV in the estuary, because of the larger tidal range

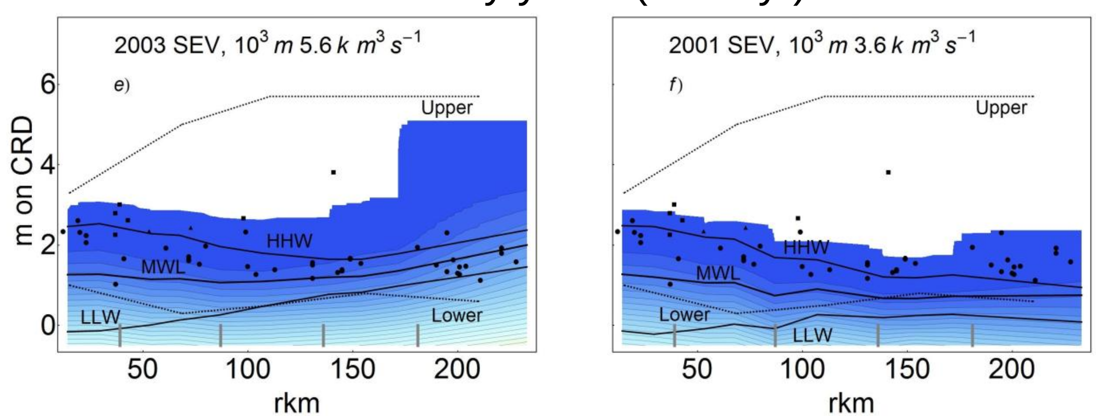
SEV for wet years ($10^3$m/yr):




SEV for typical years ($10^3$m/yr):



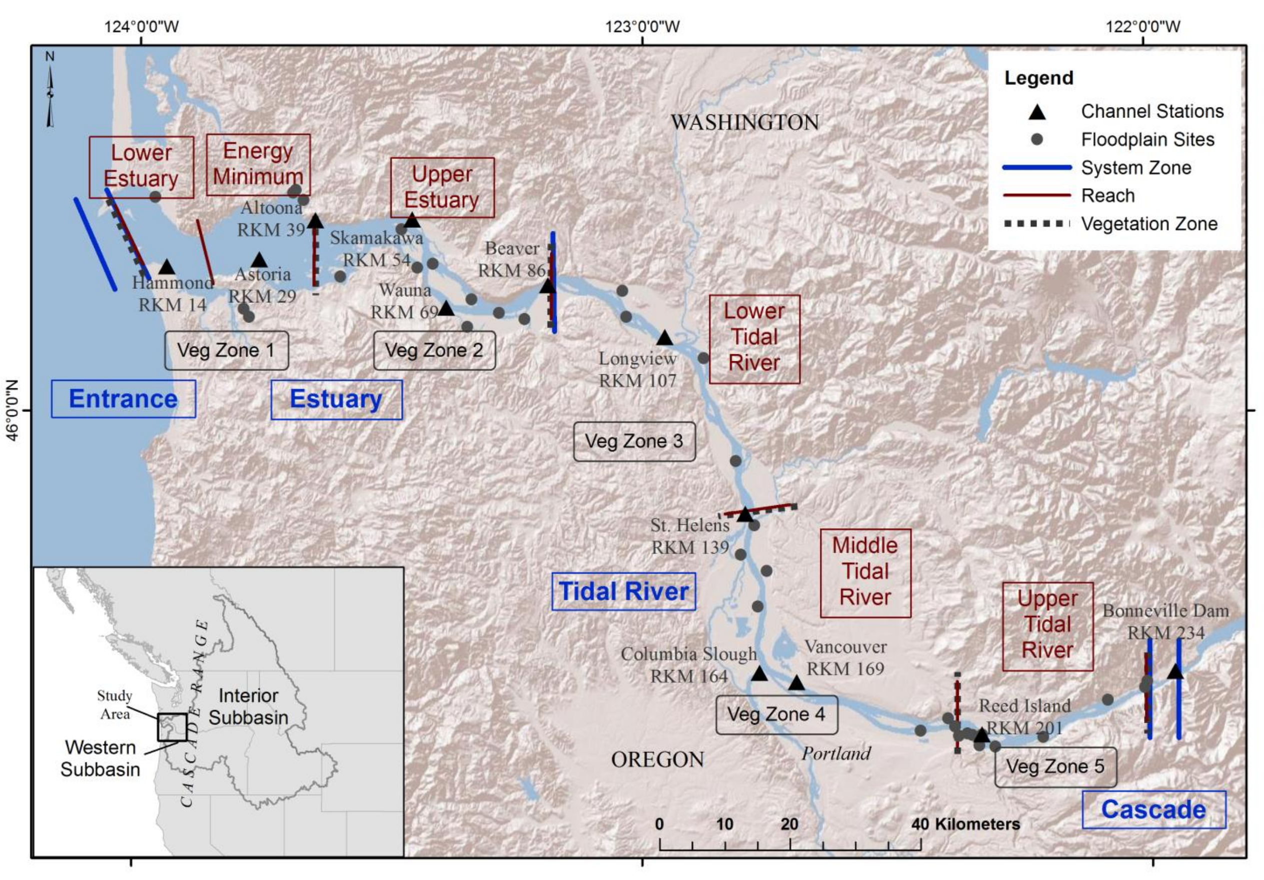

SEV for dry years ($10^3$m/yr):




Dots give marsh elevations
Solid lines give LLW, MWL and HHW
Dotted lines = marsh elevation range by zone

# Application: System Zonation –

- Zones are based on physical processes & hard constraints (geologic & man-made)
- Our zonation is similar to broader levels of the Simenstad et al. approach, but we generally don’t find that tributaries coincide with vegetation boundaries
- Zonation corresponds well with Borde et al. vegetation zone boundaries:
  - Entrance
  - RKM-39; upstream boundary of Energy Minimum Zone
  - Rkm-87; upstream boundary of Upper Estuary Zone
  - Rkm-139; upstream bdy of Lower Tidal River Zone
  - Western end of CR Gorge & Middle Tidal River Zone, at Rkm-201
  - Base of the Cascade Zone, landward end of the Middle Tidal River Zone, Rkm-229

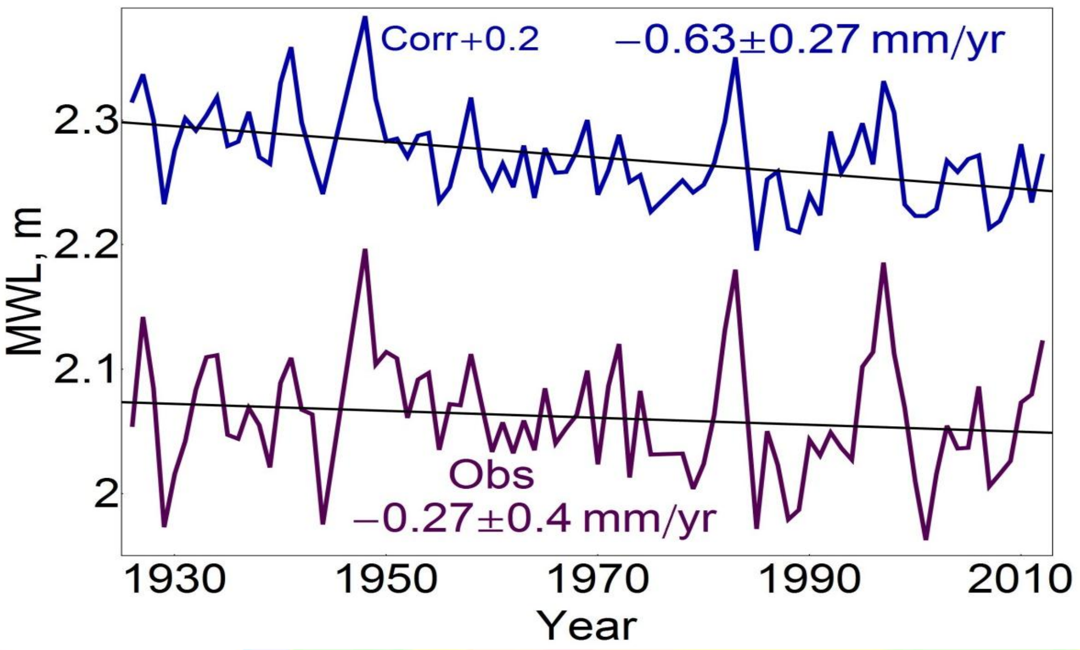


# Application: Evaluation of Past/Future Flow Changes –

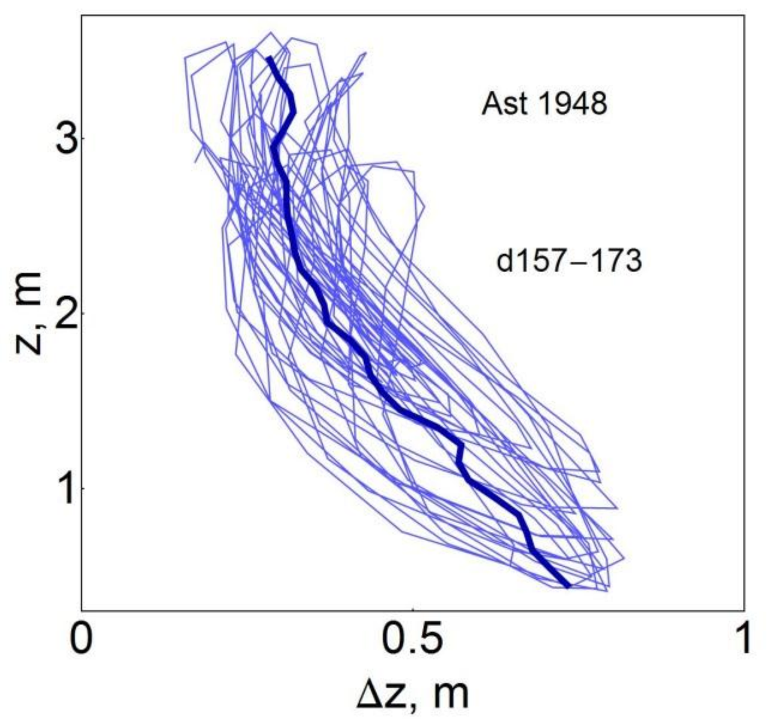
- Regression models can be run rapidly for decades
- Many phenomena and processes can be analyzed
- The flow regime has changed in the past, it will again:
  - Look at altered flow regimes, e.g., due to climate change or hydropower management
- Example questions:
  - How would treaty scenarios affect water levels and SEV?
  - What periods will be the most difficult weekends for navigation, given projected spring and summer flows?
  - How will changes in ocean tidal forcing and MSL affect the water level regime in estuary wetlands?
  - How has shallow water habitat changed over time?

# Application: Past/Future MSL changes –

- Understanding MSL rise, past and future:
  - Long tidal records are vital, but record quality is a serious concern
  - Regression models provide a powerful tool to evaluate record quality
  - For example, we discovered a previously unknown problem in the Astoria tidal record after the 1948 (Vanport) flood – record was off by 0.1-0.2m for a year!
- The 85-yr Astoria tidal record has not been used for MSL estimates, due to river flow effects; these can be corrected with regression models:
  - Considering vertical land motion from GIS of 0.69 ±1.1 mm/yr, there is no long-term trend after 1925




Biased LW values during the Vanport flood:



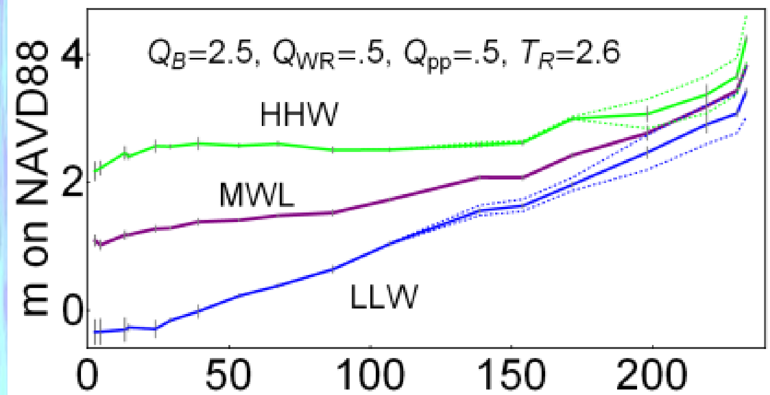
# Summary –

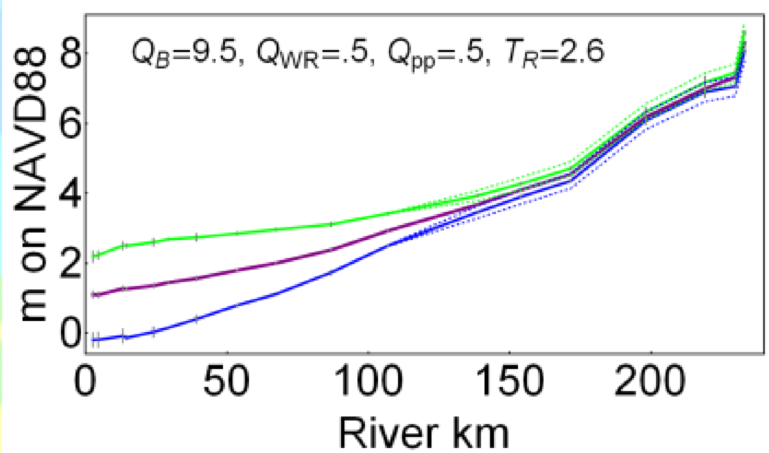
- Water levels are almost stationary near the ocean, and dominated by tides and coastal processes
- River flows and power peaking become increasingly prominant up river, making the water level record very non-stationary
- Wetland tidal records differ from channel records for several reasons
- Regression models can be used for a wide variety of analytical and prediction/hindcast tasks; they are fast and relatively accurate
- Water level analyses, other physical process data and SEV analysis suggest a system zonation largely and separate the estuary and tidal river
- SEV values vary strongly with year and river mile; they are correlated with wetland type, because wetland type varies along channel and with elevation
- Wetland SEV values can be predicted/hindcast simply from seasonal flow observations or projections and wetland elevation

# Regression Model Results (More) –

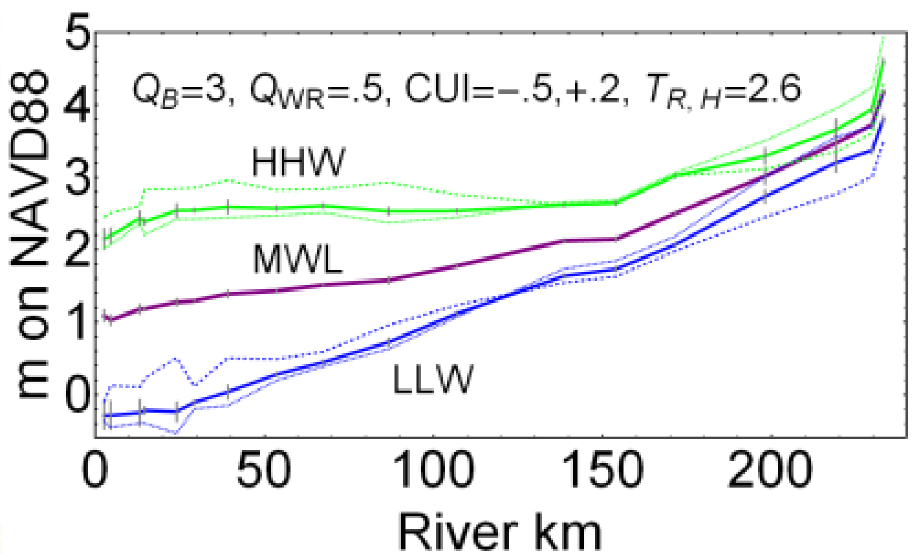
- Effects of power peaking, ±500$m^3$/s:
  - Power peaking travels as a pseudo-tide downriver
  - Near Bonneville, power peaking controls daily variations
  - Power peaking is less evident during high flow periods – it damps out, like any wave
- Effects of varying sea level pressure (SLP):
  - Downstream of Willamette confluence, low pressure raises water levels
  - Further upstream, low SLP lowers water levels, an effect of CR Gorge winds

Varying CR flow and power peaking:




Effects of SLP variations:



# Harmonic Analysis –

- Gives average tidal band structure
- Somewhat artificial, but can be interpretted
- Unrealistic constituents like $H_1$,$H_2$, and $S_1$ are very useful
  - Tell about non-stationary factors that distort results
  - $S_1$ = daily power peaking
  - $H_1$,$H_2$ result from annual cycle of river flow damping of tides
- Floodplain results are different for complicated reasons:
  - Flooring of tides by high bed elevation
  - More friction
  - Different neap-spring patterns than channel stations
  - Spatially variable effects of river flow