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What's streamflow got to do with it? A probabilistic simulation of the competing oceanographic and fluvial processes driving extreme along-river water levels

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1 Hydraulic model domain and setup

HEC-RAS model runs require detailed terrain information for the river network, including bathymetry and topography for the floodplains of interest. Topography data is sourced from a 2014 U.S Army Corps of Engineers (USACE) lidar survey (USACE, 2014). Bathymetry data is developed by blending two NOAA digital elevation models (DEM): National Geophysical Data Center's (NGDC) La Push, WA tsunami DEM (1/3 arc second; NGDC (2007)) and the coastal relief model (3 arc seconds; NGDC (2003)). These datasets, however, do not accurately resolve the channel depths of the Quillayute River inland of the coast, so a 2010 US Geological Survey (USGS)-conducted bathymetric survey of the river is also blended into the DEM (Czuba et al., 2010).

In 2010, depths of along-river cross sections and an 11 km long longitudinal profile from the Bogachiel River to the mouth of the Quillayute River were surveyed (Czuba et al., 2010). The survey of the longitudinal river profile also recorded the elevation of the water surface. Ideally, the collected bathymetry dataset would be merged directly into the existing DEM. The Quillayute River, however, is uncontrolled and meanders over time, producing a variation in the location of the main river channel between the DEM and the high-resolution USGS-collected bathymetric data. Therefore, the USGS bathymetric profiles are adjusted to match the location of the DEM channel. While a product of multiple datasets and processing steps, the final DEM provides bathymetric/topographic data with the most up-to-date channel depths for the Quillayute River (Figure 6, main text).

A series of 58 transects are extracted from the DEM using HEC-GeoRas (Ackerman, 2009) and written into a geometric data file for input into HEC-RAS. Each river transect extends across the floodplain to the 10 m contour, where applicable. Otherwise, each transect terminates at the highest point landward of the river. Because HEC-RAS computes energy loss at each transect via a frictional loss based on the Manning's equation, Manning's coefficients, an empirically derived coefficient representing resistance of flow through roughness and river sinuosity, are selected for the river channel and the floodbanks. In-channel Manning's coefficients are tuned to calibrate the model's resulting water surface elevations with that of the observed water surface data. Manning's coefficients for the rest of the computational domain (e.g., anything overbank) are estimated using 2011 Land Cover data from the Western Washington Land Cover Change Analysis project (NOAA, 2012) and visual inspection of aerial imagery and range from 0.04 (cleared land with tree stumps) - 0.1 (heavy stands of timber/medium to dense brush). These values are extracted from the HEC-RAS Hydraulic Reference Manual, Table 3-1 (Brunner, 2016). Model domain boundary conditions are chosen as the water surface elevation at the tide gauge (m; downstream boundary) and river discharge from a combination of records representing the Quillayute River watershed ($m^3 s^{-1}$; upstream boundary).

1.1 HEC-RAS model validation

In order to determine the dominant inputs to Quillayute River discharge, combined estimates of the Sol Duc and Calawah Rivers are compared to measurements taken on the Quillayute River in May 2010 (Czuba et al., 2010). Combined discharge estimates from the Sol Duc and Calawah rivers underpredict streamflow in the Quillayute River by approximately 33%. An area scaling watershed analysis (Gianfagna et al., 2015), described in the main text, found that the Bogachiel and Calawah Rivers had similar contributions. Thus the Calawah river is scaled by a factor of 2.09 to represent the Bogachiel River. Combined discharge estimates from the Sol Duc River and Bogachiel River, representing the Quillayute River, are also compared to the Quillayute discharge measurements taken during the 2010 survey. Using this methodology, the discharge estimates of the Quillayute River fall within the uncertainty of the discrete USGS measurements in most cases (Table S1).

Table S1. Quillayute River discharge measurements from the USGS survey (Czuba et al., 2010) compared to the Quillayute River discharge estimates computed by adding the Sol Duc USGS gauge measurements with the Bogachiel River discharge, estimated via scaling of the Calawah River gauge measurements. The parenthesis in the last column is the standard deviation of USGS survey measurements ($m^3 s^{-1}$).

Date of Survey	Sol Duc ($m^3 s^{-1}$)	Calawah ($m^3 s^{-1}$)	Bogachiel ($m^3 s^{-1}$) (estimated)	Quillayute ($m^3 s^{-1}$) (estimated)	Quillayute ($m^3 s^{-1}$) (measured)
4/20/2010	52	28	58	110	116 (7)
4/21/2010a	48	25	53	101	108 (1)
4/21/2010b	48	25	52	100	103 (3)
4/21/2010c	46	24	50	96	107 (1)
5/4/2010a	73	69	144	217	220 (5)
5/4/2010b	70	66	137	207	207 (4)
5/5/2010	59	51	107	166	170 (3)
5/6/2010	50	40	84	134	136 (3)

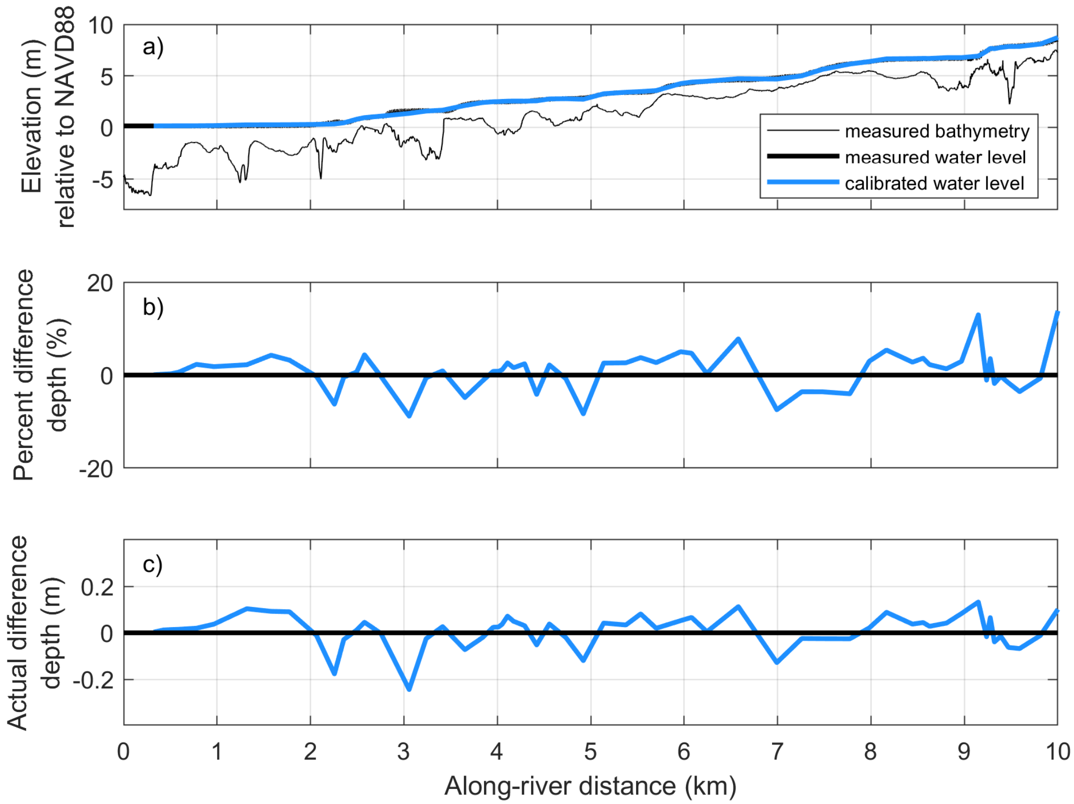

Figure S1. a) Bathymetry and longitudinal profile from the Bogachiel River to the mouth of the Quillayute River surveyed by the USGS in May of 2010 (black). The longitudinal water level for the calibrated HEC-RAS model is depicted in blue. b) Percent difference between the measured (black) and HEC-RAS modeled (blue) water level. c) Actual difference between the measured (black) and HEC-RAS modeled (blue) water level.

The longitudinal measured water surface profile allows for the verification and calibration of HEC-RAS modeled water surface elevations on the day of the survey (Figure S1). HEC-RAS is run using discharge of the watershed-scaled Bogachiel River as the upstream boundary condition during the hour of the field survey and this discharge is combined with a lateral inflow from the Sol Duc River around river km 8.5. Manning's coefficients within the main channel of the Quillayute River are calibrated to best represent the water surface elevation on the day of the USGS longitudinal survey. Final Manning's coefficients range from to 0.005 to 0.1, and are on average 0.025.

The final calibrated HEC-RAS model produces a water surface elevation with an average bias less than 1% (less than 1 cm) and an average standard deviation of approximately 5% (7.5 cm). The maximum difference between the two water surfaces is approximately 14 cm (20%). The percent difference between the depth of the observed and modeled water surface is almost always less than 10% (Figure S1).

2 Tide gauge processing

The continuous La Push tide gauge record begins in 2004, recording 12 years of water levels. This record, however, does not capture the extreme water levels occurring during the 1982/83 and 1997/98 El Niños. Therefore, water levels from the La Push tide gauge are merged with water levels from the Toke Point tide gauge (beginning in 1980, NOAA station 9440910) to create a combined water level record representing a larger range of extreme conditions. η_A and η_{SE}, water level components deterministic to the La Push tide gauge, are extended to 1980. Water level components influenced by regional or local forcings like η_{MMSLA} and η_{SS}, are compared before combining. η_{MMSLA} between the Toke Point and La Push tide gauges are similar, so Toke Point η_{MMSLA} are appended to the beginning of the La Push η_{MMSLA}. Toke Point, however, has slightly higher magnitude η_{SS} than La Push and there is a noticeable offset in the highest η_{SS} peaks. A correction is thus applied to the Toke Point η_{SS} before appending it to the beginning of the La Push η_{SS}. η_{MSL} is extended back to 1980 using relative sea level rise trends for the region. Once the two tide gauges are merged, the combined hourly tide gauge record extends from 1980 - 2016 and is 97% complete. Discharge measurements sampled at 15 minute intervals for the Calawah and Sol Duc rivers are interpolated to hourly increments to match the timing of the SWL measurements.

2.1 Removal of river-influence from the oceanographic signal

Storms tend to influence large stretches of coastline at once, and while site-specific variations in the coastline or distance from storm can drive local variations in the amplitude of η_{SS}, the overall η_{SS} signal is fairly coherent across regional tide gauges across the PNW. The river-influenced water levels are therefore isolated and removed from the La Push η_{SS} record by developing a relationship between the La Push η_{SS} and a regionally-averaged η_{SS}.

η_{SS} decomposed from the Neah Bay, Westport, Astoria, Garibaldi, and South Beach tide gauges are averaged each hour to create a regional η_{SS} record (black line; Figure S2). The standard deviation (σ) of the available η_{SS} records at each hour is used to represent the variability of η_{SS} due to local effects at each station. η_{SS} at La Push that are larger than the regional average + 2.5σ are considered anomalous to the region, and defined as river-influenced water levels (η_{Ri}). Observations flagged as larger than the regional average + 2.5σ (dashed line; Figure S2) were replaced with the regional average + σ. A value of + σ was chosen to minimize jumps in time series when substituting in a smoother dataset. While this methodology does not remove all the effects of η_{Ri} in the η_{SS} signal, it captures the majority of anomalous water levels driven by high discharge events.

η_{Ri} is produced from the difference between the original La Push η_{SS} and the η_{SS} modified described above which removes η_{SS} anomalous events. η_{Ri} occurring during low discharge events (here low is defined as less than 10 m^{3}s^{-1}, the approximate summer average discharge) is added back into the La Push η_{SS}, as it is likely not driven by river forcing. After η_{Ri} was removed from the η_{SS} signal, it is saved as a time series of river-forced water level events.

Extreme Hs and Q events at the Calawah River are determined using the Peak Over Threshold approach, where all independent daily maximum events over a defined threshold are selected. Threshold excesses are fit to non-stationary Generalized Pareto distributions, which include seasonality as a covariate. Both variables are transformed to approximately Fréchet margins. A bivariate logistic model is then used to model the dependency between the variables. To simulate, random numbers are sampled from a uniform distribution and mapped to each variable's prescribed Fréchet cumulative probability distribution function. Based on the probability of occurrence of the transformed value, the estimate is transformed back to the physical scale using the Generalized Pareto distribution if extreme, dependent on the variable's threshold. If not extreme, the estimate is transformed back to the physical scale using monthly-varying Gaussian copulas. This technique generates a synthetic record of Q at the Calawah River gauge that is seasonally varying, related to larger-scale climate variability through wave height (essentially as a proxy for storms), and carries the same dependency between variables as the observational record. Q is then multiplied by 2.09 to represent inflow from both the Bogachiel and Calawah rivers.

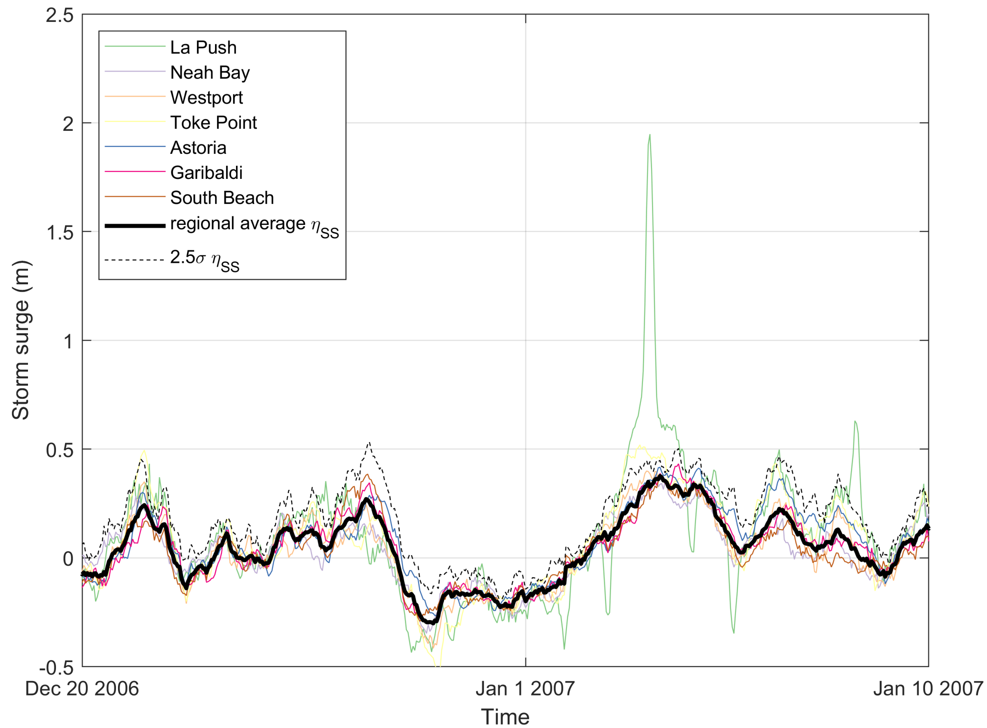

Figure S2. A comparison of storm surge (η_{SS}) decomposed from all tide gauges along the northern Washington to central Oregon coastline. The solid, black line depicts the regional average of all of the η_{SS} signals, while the dashed black line represents the regional average η_{SS} + 2.5*σ of all η_{SS} in the region. When the La Push η_{SS} exceeds the regional average η_{SS} + 2.5*σ it is removed from the record and considered river influence.

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