MEMORANDUM

Date: February 28, 2019

To: Bob Montgomery, Anchor QEA

From: Larry Karpack, P.E. and Colin Butler, EIT, WSE

Re: Chehalis River Basin Hydrologic Modeling

1.0 Introduction

This technical memorandum summarizes work performed by Watershed Science and Engineering (WSE) to develop and calibrate a hydrologic model of the Chehalis River Basin. The model extends from the headwaters of the Chehalis River upstream of Pe Ell to the mouth of the river at Grays Harbor including all tributaries to the Chehalis River. The model also includes other river basins which drain directly to Grays Harbor, including the Wishkah, Hoquiam, and Humptulips River basins. Together, the area covered by the hydrologic model comprises Water Resource Inventory Areas (WRIAs) 22 and 23 (DOE, 2018). Figure 1 shows the aerial extent of the hydrologic model.

The Chehalis River Basin hydrologic model was configured using the Distributed Hydrologic Soil Vegetation Model (DHSVM) software (Wigmosta et al, 1994). DHSVM is a gridded, physically based, distributed parameter model that provides an integrated representation of watershed processes at a user defined spatial resolution. Key data inputs to the DHSVM model include topographic, soils, land cover, and meteorological data. Development of the DHSVM model is described below in Section 3.

Meteorological inputs for the hydrologic model were provided by the University of Washington's Climate Impacts Group (CIG) and include a physically based historical data set spanning January 1981 through December 2015, as well as two long term historical/future data sets based on Global Climate Model (GCM) predictions. The meteorological data sets used in this study are described in Section 4.

The hydrologic model was calibrated and verified by comparing simulated flows against data from five USGS stream gaging stations in the basin, depicted in Figure 1 and listed in Table 1. Collectively these gages cover approximately 70% of the model domain. Preliminary calibration was conducted using an automated model parameter optimization routine to best match daily observed flows at these gaging stations for October 2006 through September 2009. Long term runs of the model were then completed and peak annual flow data for 1981 through 2015 were extracted and compared to USGS observed peak flows. Additional adjustments to model inputs were made to best match observed flows at each of the gage locations. The model calibration process and results are fully described in Section 5. The calibrated DHSVM model was then run using long term meteorological data sets to provide data for evaluation of potential climate change impacts on Chehalis River basin hydrology. This evaluation is described in Section 6.

Figure 1
Extent of DHSVM model of the Chehalis Basin

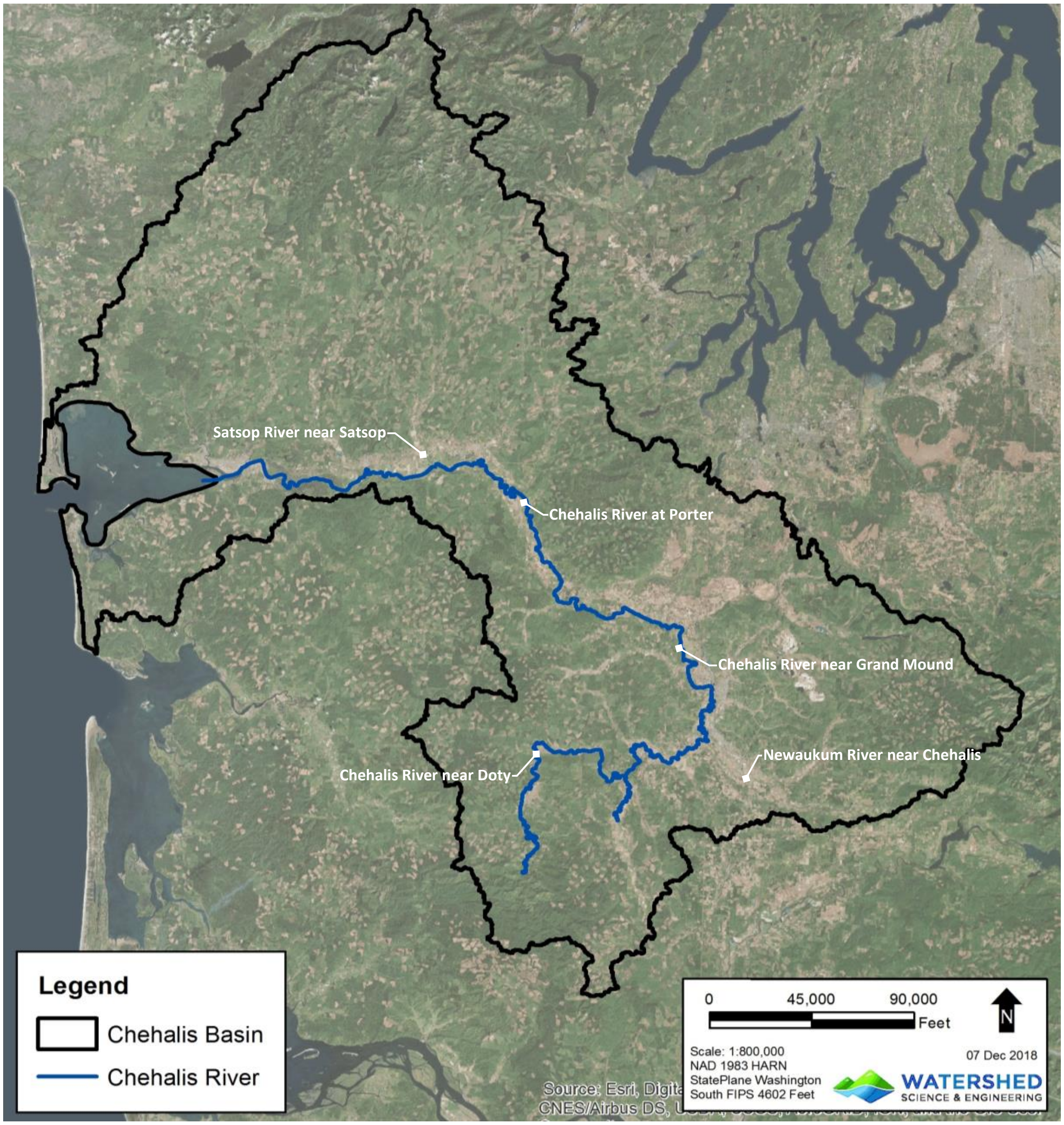


Table 1
USGS Gages Used For Hydrologic Model Calibration

USGS GAGE NAME	GAGE NUMBER	BASIN AREA	PERIOD OF RECORD
Chehalis River near Doty	12020000	113 mi^2	1939-2018
Newaukum River near Chehalis	12025000	155 mi^2	1929-2018
Satsop River near Satsop	12035000	299 mi^2	1929-2018
Chehalis River near Grand Mound	12027500	895 mi^2	1928-2018
Chehalis River at Porter	12031000	1294 mi^2	1952-2018

2.0 Background

To date, hydrologic and hydraulic analyses for the Chehalis Basin Strategy and earlier related studies have relied on USGS data to define the basin hydrology (USACE, 2014). These data provide a reasonable basis for many purposes but have limitations for certain types of analyses. Specifically, the gage data only provide information about historical periods and therefore are not useful for predicting how hydrology may change in the future, especially under changing climate conditions. Furthermore, the observed data only cover about one-third of the basin, meaning that data for the other two-thirds of the basin have to be estimated based on assumed correlations with the available gages. To address these limitations, a hydrologic model of the Chehalis River Basin is desired. A hydrologic model can be used to simulate conditions in the past, present, and future, using historical and predicted meteorological data, to provide an evaluation of the effects of potential climate change on streamflow. In addition, a hydrologic model can be used to provide information on flows throughout the basin, including both gaged and ungaged areas. A basin-wide hydrologic model can also be used to generate data to support a variety other tasks, including water quality analyses, habitat restoration design, flood reduction investigations, and sediment transport modeling. Finally, a hydrologic model can be used in the future as part of a predictive tool to forecast floods in the basin and inform early flood warning systems.

In consultation with the Department of Ecology, DHSVM was selected for hydrologic modeling this study for the following reasons:

1. It is a distributed, physically based model program facilitating the use of readily available spatially distributed input data,
2. it has been successfully applied to basins of similar size in other recent climate change studies (e.g. Skagit River),
3. it is frequently used by and has support from the hydrologic research communities at UW, WSU, and the Pacific Northwest National Lab (PNNL), and
4. a working model for the Chehalis basin is already available (as described below) and could be used as a template for development of a refined model in this project.

In previous work during the 2015-2017 biennium, a preliminary hydrologic model was developed and used to evaluate potential climate change impacts on Chehalis basin hydrology (Mauger et al, 2016). The preliminary model used DHSVM, as is being used in this study, but it did not include detailed channel routing and was only partially calibrated to observed flow data in the Doty basin. As a result, the earlier model could not be used to generate hydraulic model inputs or for many of the other applications described above.

Other hydrologic modeling programs initially considered for this study included HEC-HMS, VIC, and VELMA. HEC-HMS was previously used to model the basin upstream of Doty (WSE, 2017) to derive a preliminary spillway design flood for the proposed retention facility. That model, however, was an event based, lumped parameter model and there was concern over the robustness of HMS's computational framework for application to the much larger Chehalis River basin and its potential for continuous simulation with distributed data inputs. VIC or VELMA could have been used for this study but neither of those models includes channel routing capabilities and as such they were considered poor choices for modeling a large watershed such as the Chehalis basin.

The report sections below document the work performed in this study to develop, calibrate, and apply a comprehensive DHSVM hydrologic model of the Chehalis River Basin.

3.0 Hydrologic Model Development

Data Sources

Key inputs to the hydrologic model include topographic data, soils data, land cover data, and meteorological data. For the Chehalis Basin model the following sources of data were used:

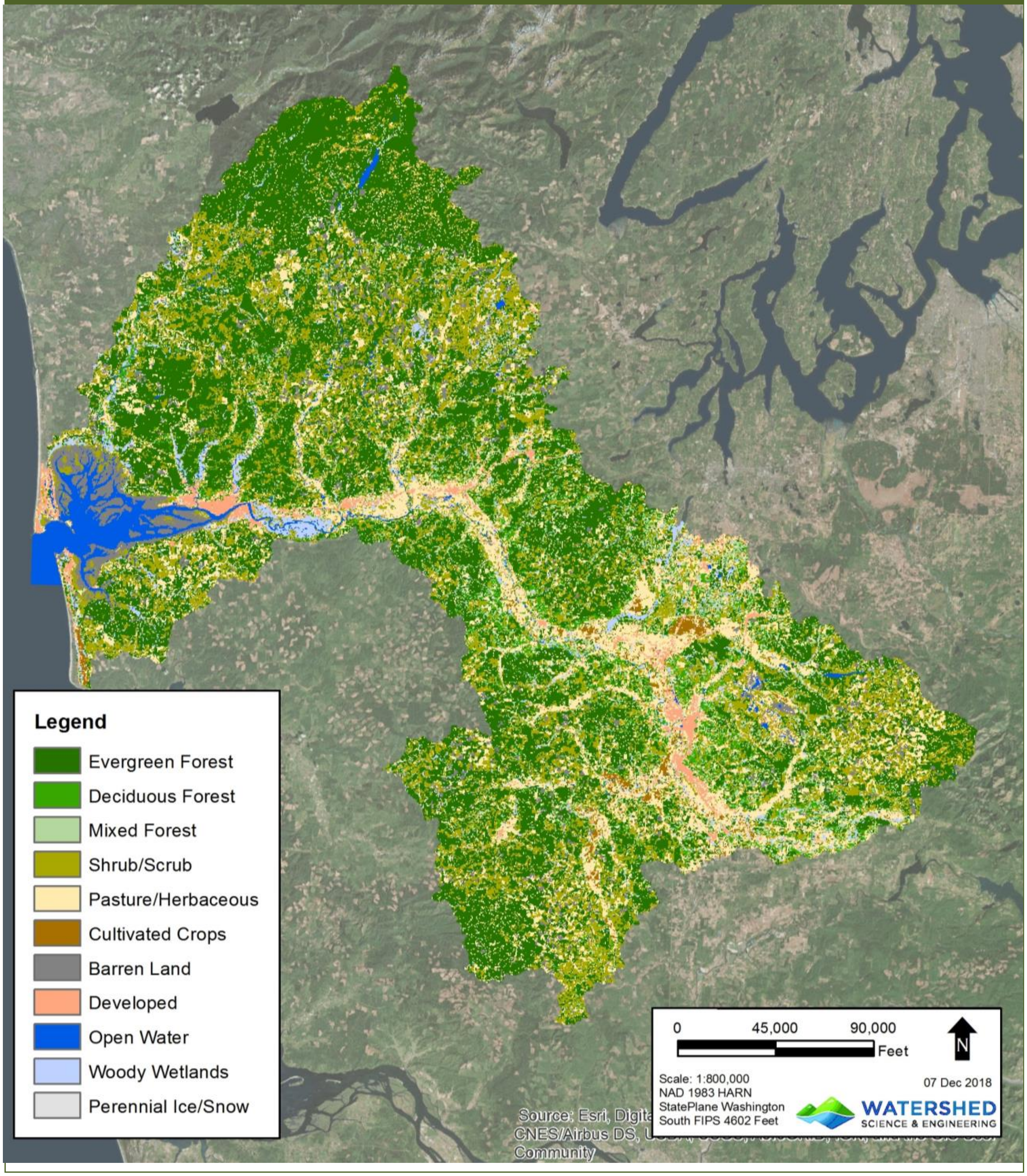
Topographic data – US Geological Survey (USGS) National Elevation Dataset 10 – and 30-meter Digital Elevation Model (DEM). Available online at https://catalog.data.gov/dataset/usgs-national-elevation-dataset-ned . Accessed April 2018

Soils Data – Natural Resources Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO) (Soil Survey Staff, NRCS, United States Department of Agriculture. Web Soil Survey. Available online at: https://websoilsurvey.nrcs.usda.gov/ Accessed April 2018). For a very small portion of the basin SSURGO data were not available. In these areas the State Soil Geographic Database (STATSGO), which is coarser than SSURGO, were used instead (obtained online using the same link as the SSURGO data). Note: SSURGO and STATSGO are based on local data and observations. They are not generated from remote sensing, unlike products such as the NLCD below.

Land Cover Data – USGS 2011 National Land Cover Dataset (https://catalog.data.gov/dataset/usgs-national-land-cover-dataset-nlcd-downloadable-data-collection). Accessed April 2018 (see Figure 2).

Meteorological Data –The meteorological data used in this study include long term historical reanalysis data covering the period 1980 – 2015, Global Climate Model (GCM) simulated data covering the period 1970 through 2099 (UW CIG, 2018), and detailed NEXRAD based precipitation data for the December 2007 Storm event (Parzybok et al, 2009). The meteorological data are described in detail below in Section 4.

Figure 2
Land Cover Classification in the Chehalis Basin



Data Development

A significant amount of data processing was required to manipulate the raw data described above for input to the DHSVM model. Data development was primarily done using GIS analysis, executable programs, python scripts, and text file editing. Specific steps in the data development included:

- Trimming topographic, soils, and land cover data to the Chehalis WRIA boundary
- Filling the USGS gridded DEM to eliminate sinks (e.g. depressions) in the terrain
- Generating flow accumulation and flow direction gridded data sets from the infilled DEM
- Creating a stream network from the flow accumulation and flow direction data and appending attributes such as elevation, slope, and flow order to each segment in the network (see Figure 3)
- Classifying stream network segments based on slope and contributing basin area
- Defining channel parameters of width, depth, and Manning's roughness for each segment class. Initial channel parameters were taken from earlier DHSVM modeling done by the UW CIG (Mauger et al, 2016).
- Categorizing soils from SSURGO and STATSGO into the twelve soil classes listed in Table 2 and shown in Figure 4. Initial hydrologic parameters for each soil class were obtained from earlier DHSVM modeling performed by the UW CIG (Mauger et al, 2016). These were subsequently adjusted through calibration as described in Section 5. Final calibrated soil parameters are shown in Appendix A.
- Mapping estimated soil depth based on slope, contributing basin area, and elevation
- Creating basin masks at key locations (Chehalis River at Doty, Newaukum River at Chehalis, Satsop River at Satsop, etc.) for model calibration
- Generating channel, interception, snow, and soil state files describing initial conditions

Table 2
Soil Types and Coverage in the Chehalis River Basin

	PERCENT OF EACH SUB-BASIN BY SOIL TYPE			
SOIL TYPE	DOTY	NEWAUKUM	SATSOP	FULL BASIN
SAND	0%	0%	1%	2%
LOAMY SAND	0%	2%	14%	5%
SANDY LOAM	3%	0%	36%	12%
SILTY LOAM	26%	16%	32%	34%
LOAM	49%	16%	2%	11%
SANDY CLAY LOAM	-	-	-	0%
SILTY CLAY LOAM	14%	4%	9%	11%
CLAY LOAM	1%	14%	0%	8%
SILTY CLAY	6%	47%	0%	11%
CLAY	-	-	0%	2%
WATER (as clay)	0%	0%	1%	3%
OTHER (as SCL)	0%	0%	4%	3%

Figure 3
DHSVM Stream Network

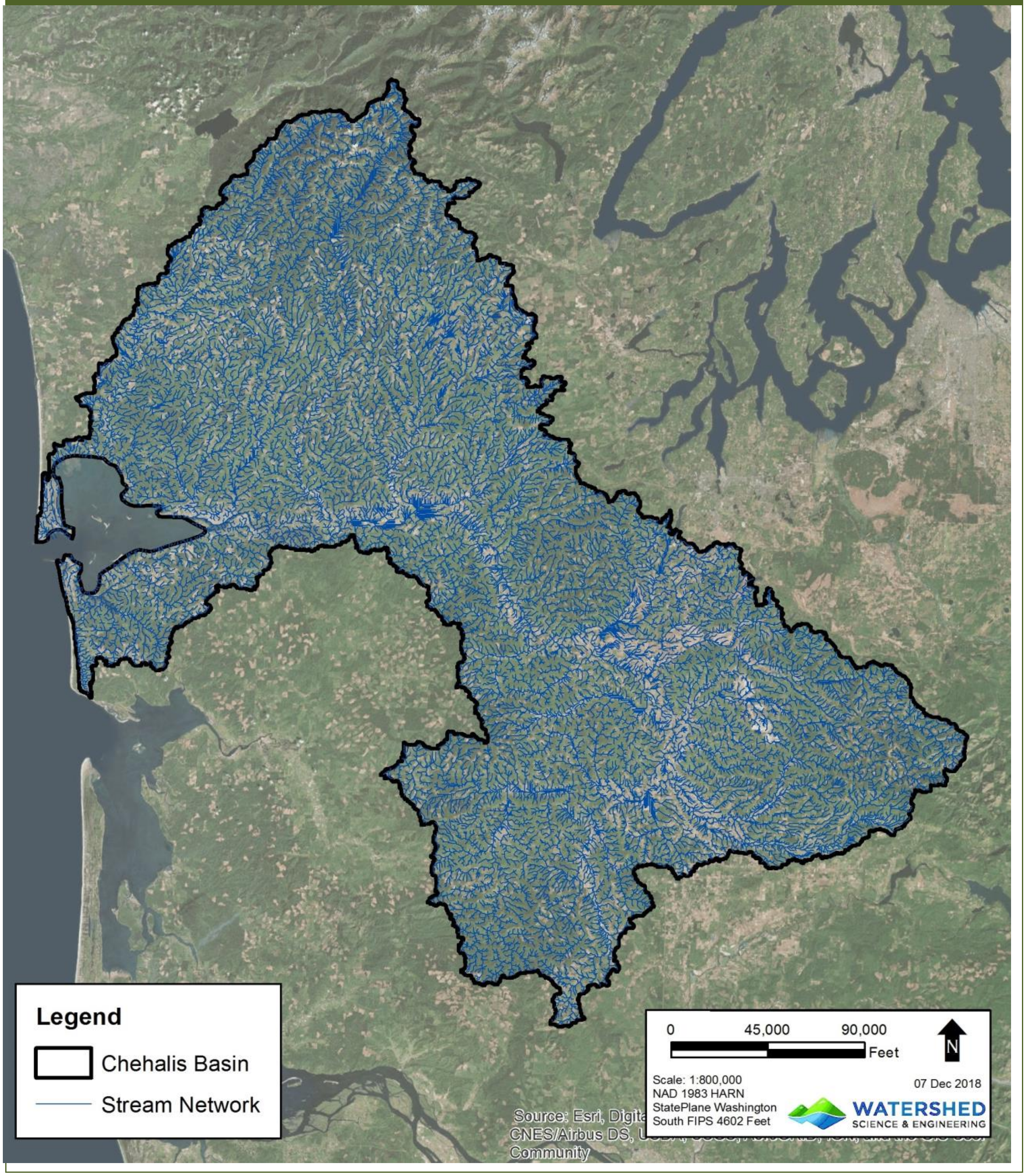
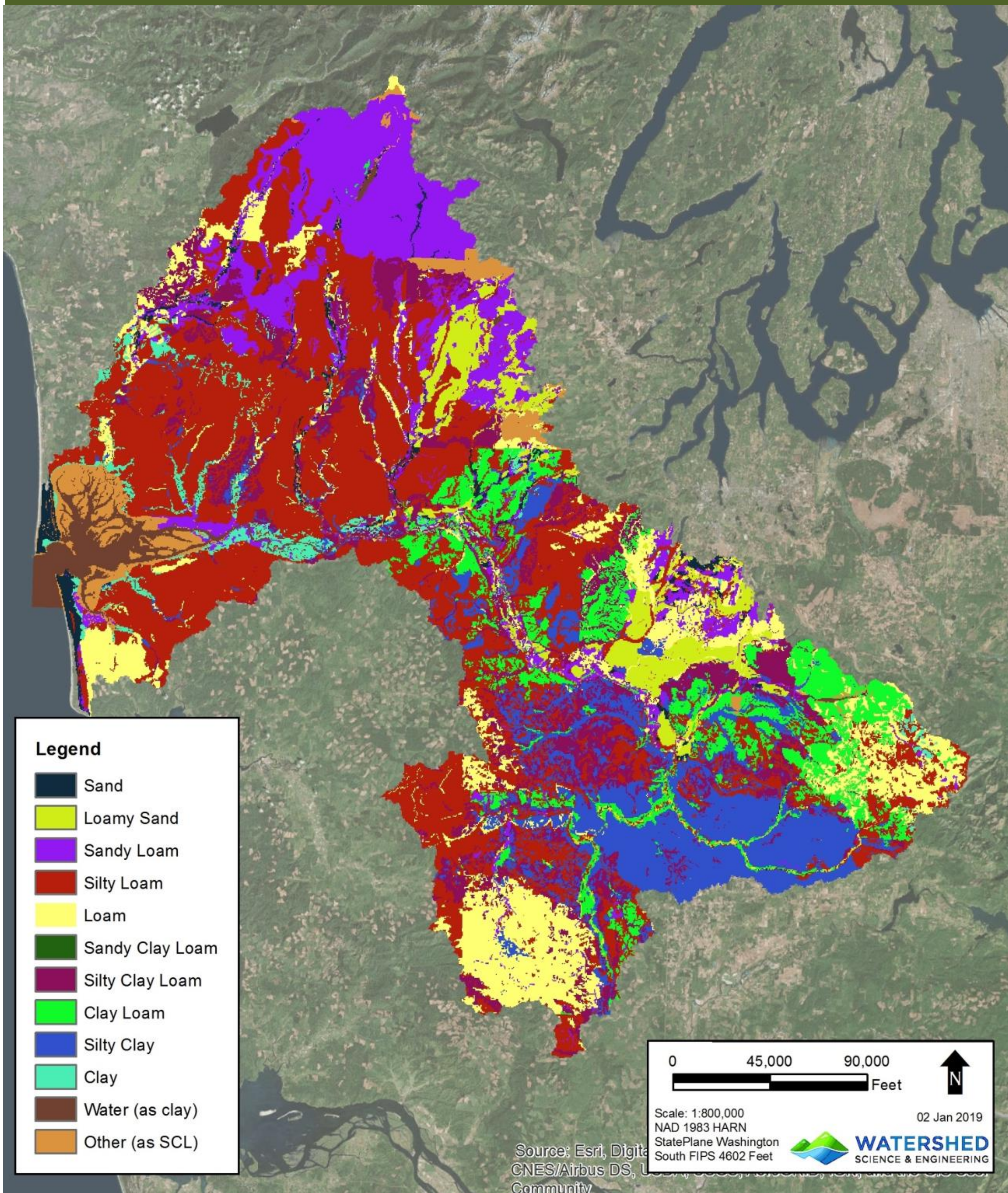


Figure 4
Chehalis Basin Soil Types



4.0 Meteorological Data

Meteorological data required by DHSVM includes spatially and temporally distributed air temperature (°C), wind speed (m/s), relative humidity (%), incoming shortwave radiation (W/m^2), incoming longwave radiation (W/m^2), and precipitation (m) data. Meteorological data for the current modeling effort were developed by downscaling historical observations and future global climate model simulations. Data were dynamically downscaled to the Chehalis basin using the Weather Research and Forecasting (WRF) model. Past work by the UW CIG found that dynamically downscaling data, as opposed to statistically downscaling, is necessary to capture interactions between weather systems and complex terrain in the Pacific Northwest (e.g., Salathé et al, 2014). Three new dynamically-downscaled climate simulations, reflecting recent advances in both regional-scale and global climate modeling, were used in this study (see Table 3). The first of these was developed by the Pacific Northwest National Lab (PNNL) and the latter two by the University of Washington Climate Impacts Group (UW CIG; Mauger et al, 2018).

Table 3
Meteorological driving data sets used in this study

DATA SOURCE	TIME PERIOD	MODEL	RESOLUTION	TIME STEP	DRIVING DATASET
PNNL	1980-2015	WRF	6 km	1 hour	NARR[1]
UW CIG	1970-2099	WRF	12 km	1 hour	GFDL CM3, RCP 8.5[2]
UW CIG	1970-2099	WRF	12 km	1 hour	ACCESS 1.0, RCP 4.5[3]

[1] North American Regional Reanalysis
[2] A global climate model and scenario representing a high-end estimate of future changes
[3] A global climate model and scenario representing a low-end estimate of future changes

Each meteorological data set covered the entire Chehalis River Basin and was generated at an hourly time step. The spatial resolution and period of record for each data set is listed in Table 3. The spatial distributions of meteorological data across the basin are shown in Figures 5 and 6. The PNNL data are based on a historical reanalysis, meaning the data are intended to replicate historical observations such as timing, duration, and intensities of storms (i.e. specific historical storms in the Chehalis River Basin should be replicated in the data set). The future climate projections produced by UW CIG, on the other hand, are based on "free running" global climate model simulations. This means that they should match key statistical properties of historical periods (i.e. annual and seasonal precipitation amounts, storm durations and intensities) but that they will neither match the timing of historical events (i.e. specific historical storms) nor replicate the timing of observed historical cycles (i.e. ENSO, PDO).

As will be described later in this document preliminary calibration runs of the DHSVM model indicated that the PNNL precipitation data might be underestimating some historical storm events while overestimating others. Furthermore initial hydrologic modeling indicated that there might be a spatial bias in the PNNL data. To evaluate this issue WSE reviewed the PNNL precipitation data and compared mean annual precipitation in the PNNL data set at each grid point in Figure 5 to mean annual precipitation (MAP) obtained from PRISM (Parameter-elevation Relationships on Independent Slopes

Model) (Daly, et al, 2008). This comparison was done for the 1981 – 2010 climate epoch. The evaluation revealed significant differences between the PNNL and PRISM mean annual precipitation data, particularly for areas in the lower basin downstream of Grand Mound. Figure 7 shows the computed relative percent differences between PRISM and PNNL mean annual precipitation. Negative values indicate that the PNNL mean annual precipitation is lower than the corresponding PRISM value while positive values indicate that PNNL is greater than PRISM. As shown in Figure 7, the relative differences range from negative 51.6% to positive 46.6% with a general trend toward lower values in the PNNL data, especially for the Satsop River Basin and other drainages in the northwest portion of the Chehalis Basin (WRIA 22).

In addition to the comparisons to PRISM data, WSE compared the PNNL precipitation to observed data from several rain gages in the upper Chehalis River Basin as well as the gage at Chehalis Airport. This comparison, summarized in Table 4, shows that average annual precipitation from the PNNL data are, on average, approximately 83% of the observed totals with results at individual gages ranging from 77% to 94% of the observed mean annual totals. PRISM mean annual precipitation data were also compared to the observed data at these gages and showed a much closer correlation, averaging approximately 96% of the gaged values with individual gage results ranging from 82% to 120% of observed values.

Table 4

Comparison of Mean Annual Precipitation for Chehalis Basin Precipitation Gages versus PNNL and PRISM

	Rock Creek		Brooklyn		Thrash Creek		Huckleberry Ridge		Abernathy Mntn		Chehalis AP		All Sites
Lat/Long	46.53, -123.40		46.73, -123.55		46.48, -123.30		46.50, -123.38		46.34, -123.08		46.68, -122.98		
Elevation	1424 feet		1020 feet		800 feet		2425 feet		2900 feet		175 feet		
Year	**Precip (in)**		**Precip (in)**		**Precip (in)**		**Precip (in)**		**Precip (in)**		**Precip (in)**		
WY 2013	105.5		72.4		111.1		112.0		39.5		46.2		
WY 2014	76.5		57.7		81.6		87.6		82.4		39.8		
WY 2015	77.3		61.2		77.0		98.0		80.1		39.9		
WY 2016	122.4		80.6		108.1		129.0		131.0		57.2		
WY 2017	138.9		90.1		127.8		144.4		116.8		58.7		
WY 2018	103.7		75.4		97.9		120.3		92.4		45.4		
Average	(in/yr)	% of gage	(in/yr)	% of gage	(in/yr)	% of gage	(in/yr)	% of gage	(in/yr)	% of gage	(in/yr)	% of gage	
Gage	104.0		72.9		100.6		115.2		100.5		47.9		**Average**
PRISM	103.5	99%	87.7	120%	75.0	75%	118.7	103%	82.7	82%	46.6	97%	**96%**
WRF	80.3	77%	56.4	77%	89.6	89%	93.4	81%	79.2	79%	44.9	94%	**83%**

Another check on the accuracy of the PNNL data was made by comparing the PNNL four day precipitation totals for the December 2007 flood event to detailed precipitation data for that event developed by MetStat (Parzybok et al, 2009). The MetStat data is based on a detailed storm reanalysis using NEXRAD radar and observations at hundreds of gaging stations and is thus considered to be as accurate a record as possible. The storm total comparisons showed that the PNNL precipitation totals were generally much lower than the MetStat totals, on average about 70% of the MetStat values, with even lower ratios in the Chehalis River basin upstream of Doty. Unfortunately, MetStat data are not available for any other events in the historical period so a similar comparison cannot be made for other events. However, comparisons for the December 2007 event, the flood of record across much of the

Chehalis River basin, indicate that the PNNL data may not accurately represent historical storm event precipitation.

Limited testing was conducted with the hydrologic model to see if adjustments could be made to the PNNL data to improve confidence in the DHSVM model calibration. In one test PNNL precipitation data for the four day period of the December 2007 storm event were replaced with the MetStat data described above and the DHSVM model was rerun for this event. These simulations showed much better replication of USGS reported peak flows at most gages, indicating that the model's performance is greatly improved with accurate precipitation data. This analysis is described in more detail in Section 5. Unfortunately the MetStat data are only available for the single storm event and thus the overall model calibration cannot be improved using these data.

In a second test the PNNL hourly precipitation data were scaled based on the ratio of PRISM to PNNL mean annual precipitation at each grid cell and the DHSVM model was rerun to evaluate the effect on simulated flows. This test showed that precipitation scaling (aka bias correction) can have a significant effect on the results of the hydrologic modeling but it also found that using a single scaling factor across all durations did not universally improve the calibration. The calibration at some locations, such as the Satsop gage, was improved while the calibration at other locations was unaffected or worsened. To improve the calibration would require developing a robust and defensible precipitation bias correction approach and then using the corrected data to comprehensively recalibrate the hydrologic model. Unfortunately there was neither time nor resources to do either of those tasks in the current study. The UW CIG is currently reviewing precipitation bias and other issues for all of the meteorological data sets being used in this study and will be reporting on that separately. It is anticipated that future hydrologic modeling efforts could use information developed by the CIG to improve the model calibration and application.

Overall, the precipitation data analyses described above indicate that the PNNL data may be generally biased low on an annual basis and may not closely match observed precipitation for specific storm events. However, despite this finding, the PNNL data are currently the only spatially distributed hourly historical meteorological data set available for the Chehalis River Basin[1] and were therefore used for the hydrologic model calibration described in Section 5

[1] PRISM data is only available at daily or monthly time steps and thus cannot be applied directly to hourly DHSVM modeling. Furthermore PRISM is developed using complex rainfall interpolation between existing meteorological stations, meaning its accuracy is dependent on the density and quality of station data, which are limited in the Chehalis basin. Finally, in addition to precipitation data the DHSVM model requires other meteorological inputs including relative humidity and solar radiation that are not available from PRISM. For these reasons, PRISM was only used for comparing mean annual precipitation to that of the PNNL dataset for the 1981-2010 period of overlap and not directly for DHSVM modeling.

Figure 5
Distributed PNNL Historic Met Data at 6km Resolution

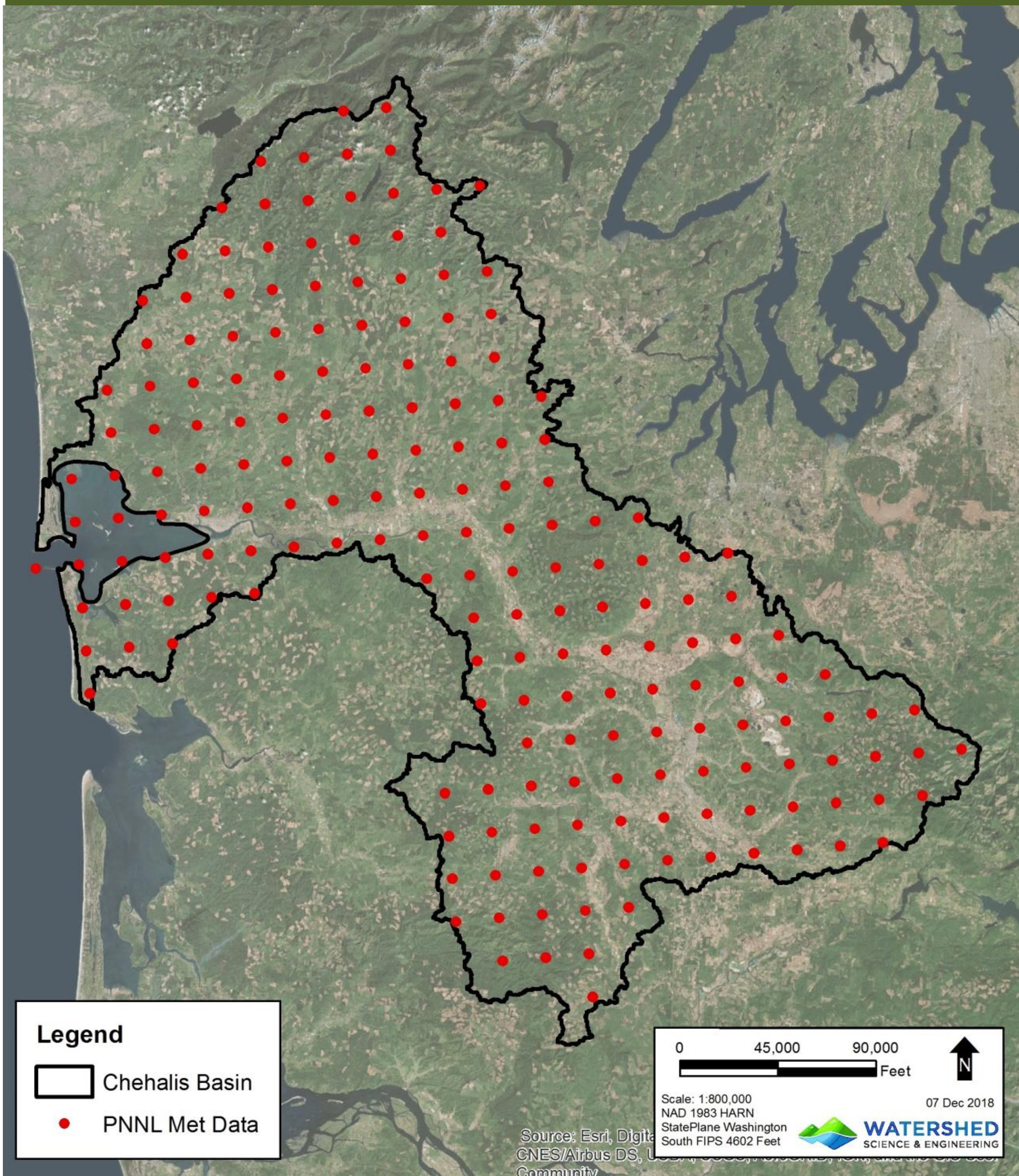


Figure 6
Distributed ACCESS RCP4.5 and GFDL RCP8.5 Climate Met Data at 12km Resolution

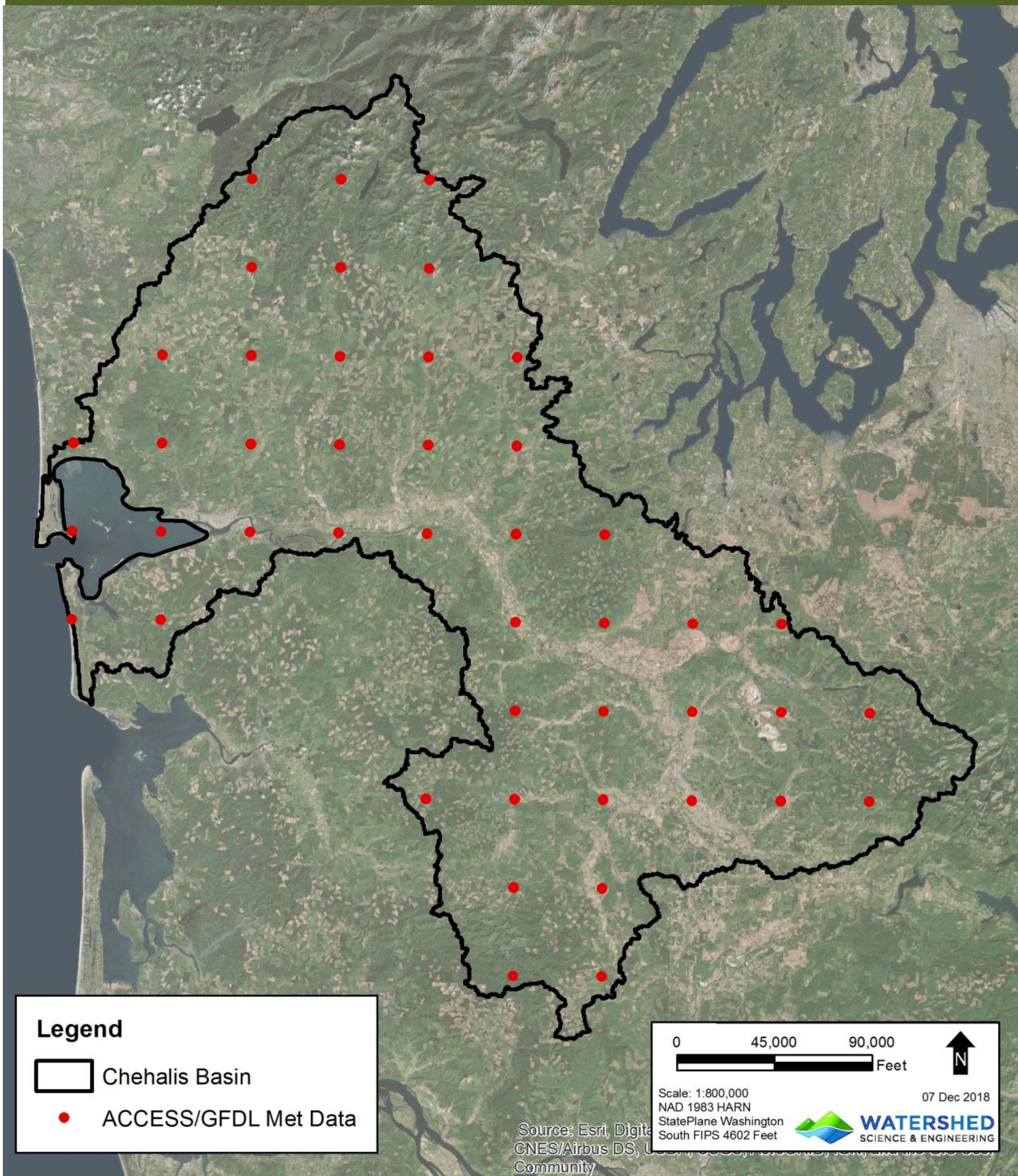
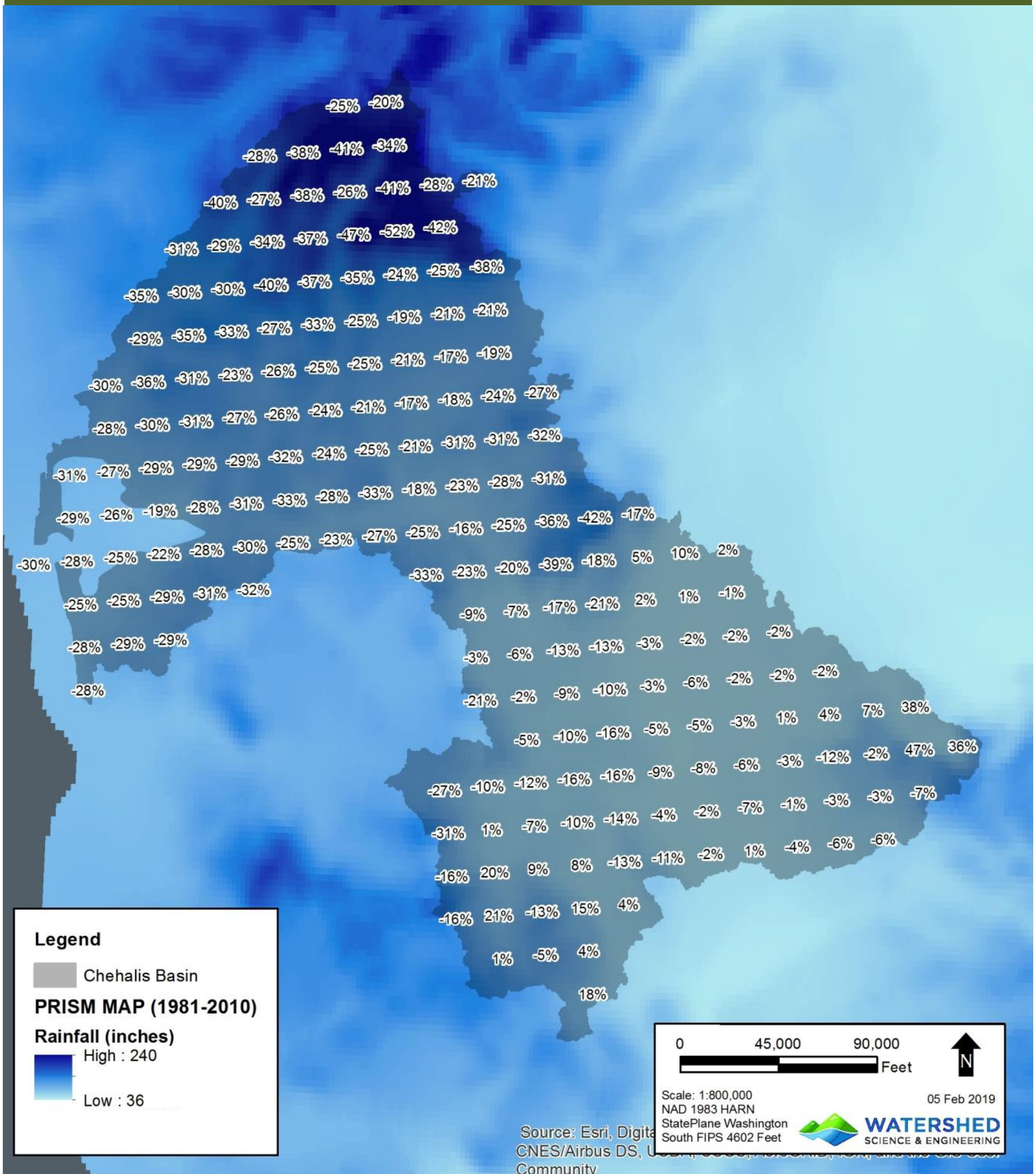


Figure 7
Percent Difference in Mean Annual Precipitation (1981 – 2010) – PNNL minus PRISM (%)



5.0 Model Calibration

MOCOM-UA Calibration (2006 – 2009)

A multi-objective complex evolution (MOCOM-UA) calibration approach was used to improve the efficiency and outcome of the calibration process. This approach systematically adjusts multiple model input parameters and refines the input values by iteratively comparing model outputs to calibration data (Yapo, et al, 1998). The MOCOM-UA routine operates by creating a parameter space within user-specified bounds for each of the calibration parameters, such as soil properties, then generating combinations of unique values for each of the calibration parameters and applying them in the DHSVM model. The routine extracts simulated streamflow output from the model at a user-specified location and calculates error statistics relative to the calibration data set (e.g. USGS observations) for the run. Each run produces a summary that includes model run, input parameter values, and error statistics. The routine randomly generates input parameter values within the user-specified bounds until there are a sufficient number of runs to rank those with the best error statistics. Once the runs are ranked, the routine creates a smaller parameter space from the parameter values associated with the ranked runs and continues to generate new sets of parameter values within that space. These contraction and analysis steps continue until the error statistics for the set of ranked runs converge and the resulting input parameter values are considered the best fit parameters.

The MOCOM-UA routine was configured to run for a three water-year period from October 2006 to September 2009, which included the significant historical floods of December 2007 and January 2009 and also provided sufficient data to allow an evaluation of annual and seasonal model performance. The routine compared streamflow output from each model run against USGS daily streamflow data at each of the calibration gage locations and ranked the top runs for each location based on two measures of calibration performance: root mean square error (RMSE) and Nash-Sutcliffe model efficiency coefficient.

The MOCOM-UA routine was applied first to the basin upstream of the USGS Chehalis River near Doty stream gage and used to calibrate lateral conductivity and exponential decrease (of lateral conductivity with depth) for the predominant soil type in the Doty basin, Loam (Soil 6), in addition to precipitation lapse rate (i.e. change in rainfall as a function of change in elevation). Note that precipitation lapse rate was only calibrated for the Doty basin and subsequently used throughout the watershed as the resultant value was reasonable and there is no physical basis to expect rainfall lapse rate to differ throughout the basin. Furthermore the lapse rate would not actually have much effect on the precipitation inputs or calibration results as the gridded meteorological data are quite densely distributed and therefore do not require much elevation adjustment. With these three parameters calibrated and incorporated into the DHSVM configuration, the MOCOM routine was then applied to the basin upstream of the USGS Newaukum River near Chehalis gage to calibrate lateral conductivity, exponential decrease, and maximum infiltration for the predominant soil type in that basin, Silty Clay (Soil 11). Following this second calibration step, the calibrated parameters for Soil 11 were incorporated into the DHSVM configuration such that the soil parameters for Loam and Silty Clay (Soils 6 and 11) were set in the DHSVM configuration. The MOCOM-UA routine was then applied to calibrate soil lateral conductivity, exponential decrease, and maximum infiltration for Silty Loam (Soil 4), the predominant soil type in the basin upstream of the USGS Satsop River near Satsop gage. The process described above resulted in detailed calibration of key soil parameters for three soils types, chosen because they were the dominant soil type in the three calibration sub-basins and together these soil types cover a substantial portion (56%) of the overall Chehalis River Basin.

Sensitivity Testing of Other Soil Properties

As described above, the MOCOM-UA routine determined soil parameters that produced the best fit to the calibration data for three key parameters for the three predominant soils types in the basin. Sensitivity tests were then conducted to see if adjustment of other model parameters or adjustment of parameters for other soil classes could improve the model performance, particularly for individual flood events. Adjustments to soil depth, vertical conductivity, lateral conductivity, exponential decay of lateral conductivity, maximum infiltration, and soil depth threshold were applied to evaluate their effects on streamflow at the USGS gage locations. These sensitivity tests found that the model output was relatively insensitive to these parameters and that additional refinement would not significantly improve the accuracy of the simulation results. The lone exception to this was the soil depth parameter which was found to have some effect on simulated peak runoff, particularly during extreme flood events.

Final Adjustment of Soil and Channel Properties

As noted above, the only soil parameter in DHSVM other than the MOCOM calibration parameters that was found to have more than a minimal effect on the simulation results was soil depth. Tests with a range of uniform minimum and maximum soil depths as well as various weighting schemes for generating spatially distributed soil depths determined that soil depth could moderately affect peak flows, with shallower soil causing generally higher discharges and deeper soil leading to a more muted response. However due to initial modeling indicating that peak runoff for some events in certain basins was under-simulated and for other storms in other basins was over-simulated, no alternative set of soil depths based on basin characteristics (e.g. elevation, catchment area) could be found to universally improve the model calibration.

In addition to soil depth, it was determined that channel characteristics, which define how flows are routed down the basin, had a significant effect on simulated peak discharges. Within DHSVM, stream segments were first classified based on slope and contributing basin area. Hydraulic properties of the channels including width, depth, and roughness were then initially set based on previous work done by the CIG. After reviewing the initial simulation results, WSE adjusted channel characteristics in DHSVM to better match the Chehalis River hydraulic model (WSE, 2018). The stream segment classifications and channel properties were then further revised through manual adjustments to provide the best fit between simulated and observed peak flows. This process resulted in higher degree of spatial variation in stream segment classification compared to the previous modeling by the CIG and better correlation between observed and modeled channel properties throughout the basin. The calibrated channel properties resulted in simulated peaks more closely matching USGS gage data at all five calibration locations.

Table 5 summarizes the results of the model calibration. Included in the table are comparisons of mean annual flow from the USGS gage data versus the simulation results. These show that three of the calibration sites are within 10% of the observed flows while the sites at Doty and on the Satsop River are about 20% low. For both of these sites this difference is considered to be primarily a function of the PNNL precipitation data which shows a large negative bias in both of these basins. For the Doty site in particular the flow differences during the December 2007 event alone were found to account for almost 30% of the mean annual flow difference shown in Table 5 (i.e. if this event is removed from the analysis the mean annual flow error is reduced to -17%). Table 5 also lists the Root Mean Square Error (RMSE) and Nash-Sutcliffe efficiency (NSE) coefficient from the final calibration runs for the basins where the MOCOM-UA tool was used. NSE is a goodness of fit statistic commonly used to judge hydrologic model calibration performance. NSE can range from negative infinity to 1; a value of 1 denotes a perfect calibration. Values above about 0.7 are generally considered decent (McKane, 2019). In the case of the three basins calibrated using the MOCOM-UA approach the NSE is greater than 0.8 implying a reasonably good calibration.

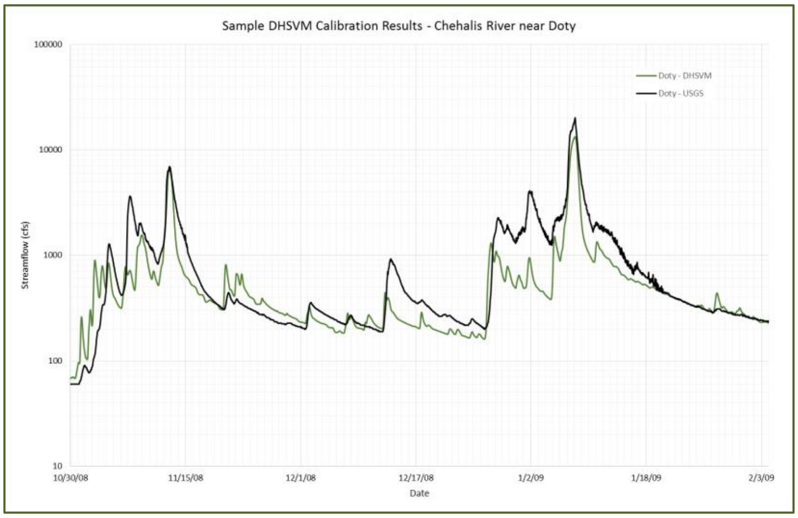
Table 5
Calibration Results

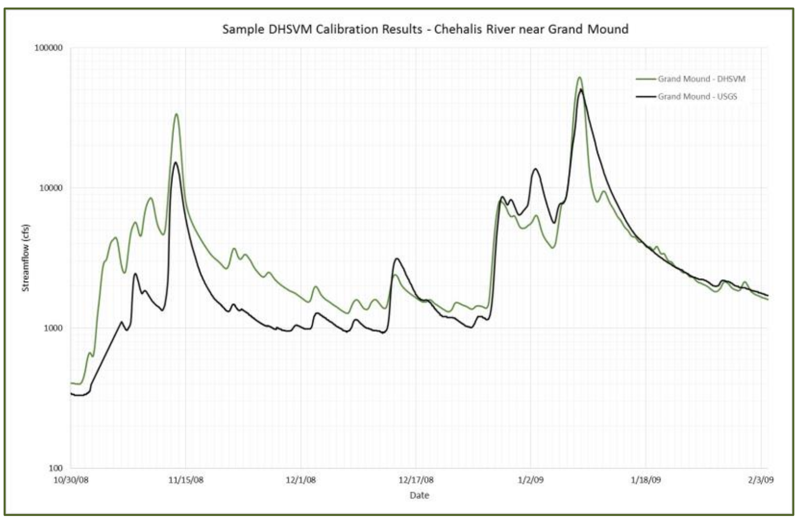
	MEAN ANNUAL FLOW				
USGS GAGE LOCATION	USGS	DHSVM	% DIFF	RMSE[1]	NASH-SUTCLIFFE[1]
Chehalis River near Doty	619	477	-22.9%	402	0.80
Newaukum River near Chehalis	539	551	+2.2%	405	0.81
Satsop River near Satsop	1,959	1,558	-20.5%	1129	0.84
Chehalis River near Grand Mound	2,754	3,025	+9.8%		
Chehalis River at Porter	4,037	4,251	+5.3%		

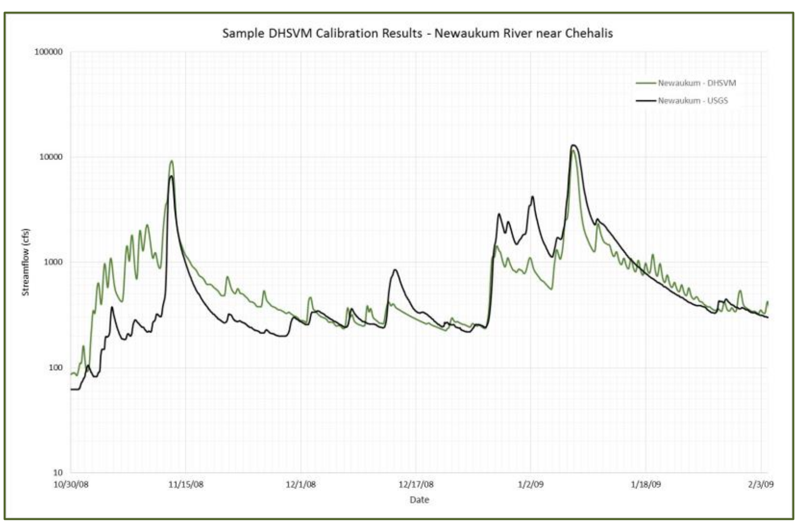
Note: [1]RMSE and Nash Sutcliffe Efficiency were only calculated for the MOCOM calibration basins.

Figure 8 shows examples of the model calibration for the period November 1, 2008 through February 1, 2009, a period which included several large floods including the extreme flood of January 2009. Plots are provided for the USGS gages near Doty and Grand Mound on the Chehalis River and near Chehalis on the Newaukum River. As seen in Figure 8 the model does a reasonably good job of mimicking the rise and fall of each flood event and also generally performs well in terms of the simulated flood peaks. It is surmised that the rainfall data for this period is generally good as the modeled flows seem to respond to each event in the observed record and the simulated peaks are similar to the observed values. This is particularly true for the extreme flood of January 2009 where each of the simulated peak flows are within about 10% of the corresponding observed values.

Figure 8
Example Plots for Final DHSVM Calibration Runs







Frequency Analysis

Once the channel properties and soil parameters were calibrated as described previously, the DHSVM model was configured and run for the full Chehalis River Basin for the period January 1981 through December 2015 using the PNNL meteorological data. Hourly streamflow data for each of the five gage locations were extracted and imported to HEC-DSS. Observed peak annual streamflows for each gage were also downloaded from the USGS website and imported to DSS. Observed and simulated peak annual streamflows were then subjected to frequency analysis and flood flow quantiles were computed. The results of this analysis are summarized in Table 6 and flood frequency plots for each gage location are provided in Figures 9 through 13.

As seen in Table 6 and Figures 9 through 13 the approximate magnitudes and general trends in the frequency analyses are captured fairly well with a few notable exceptions. For the gage on the Chehalis River near Doty the upper tail of the frequency curve for simulated data is quite a bit lower than the curve based on USGS data. The gage on the Newaukum River near Chehalis shows just the opposite result with the upper tail of the curve being significantly oversimulated. For the Satsop River near Satsop the shape of the curve based on USGS data is matched quite well but all of the values are low, by about 20%. Interestingly this is the same amount that the mean annual flow is low and is also approximately the same as the precipitation differences shown in Figure 7, indicating that a negative precipitation bias may be the primary cause of the undersimulations in that basin.

Table 6
Flood Frequency Analysis Results

	USGS OBSERVED FLOWS				DHSVM SIMULATED FLOWS			
USGS GAGE LOCATION	2-YR	10-YR	25-YR	100-YR	2-YR	10-YR	25-YR	100-YR
Chehalis River near Doty	11,940	24,840	31,440	41,050	9,940	14,430	16,480	19,320
Newaukum River near Chehalis	7,700	12,000	13,640	15,570	7,850	14,930	19,390	27,280
Satsop River near Satsop	30,240	45,640	52,820	63,000	23,630	36,000	41,420	48,720
Chehalis River near Grand Mound	27,600	52,760	65,450	84,000	38,800	62,070	72,200	85,650
Chehalis River at Porter	31,200	55,760	67,200	83,000	43,400	66,990	77,400	91,500

Figure 9
Frequency Curve for Peak Annual Flows on Chehalis River at Doty

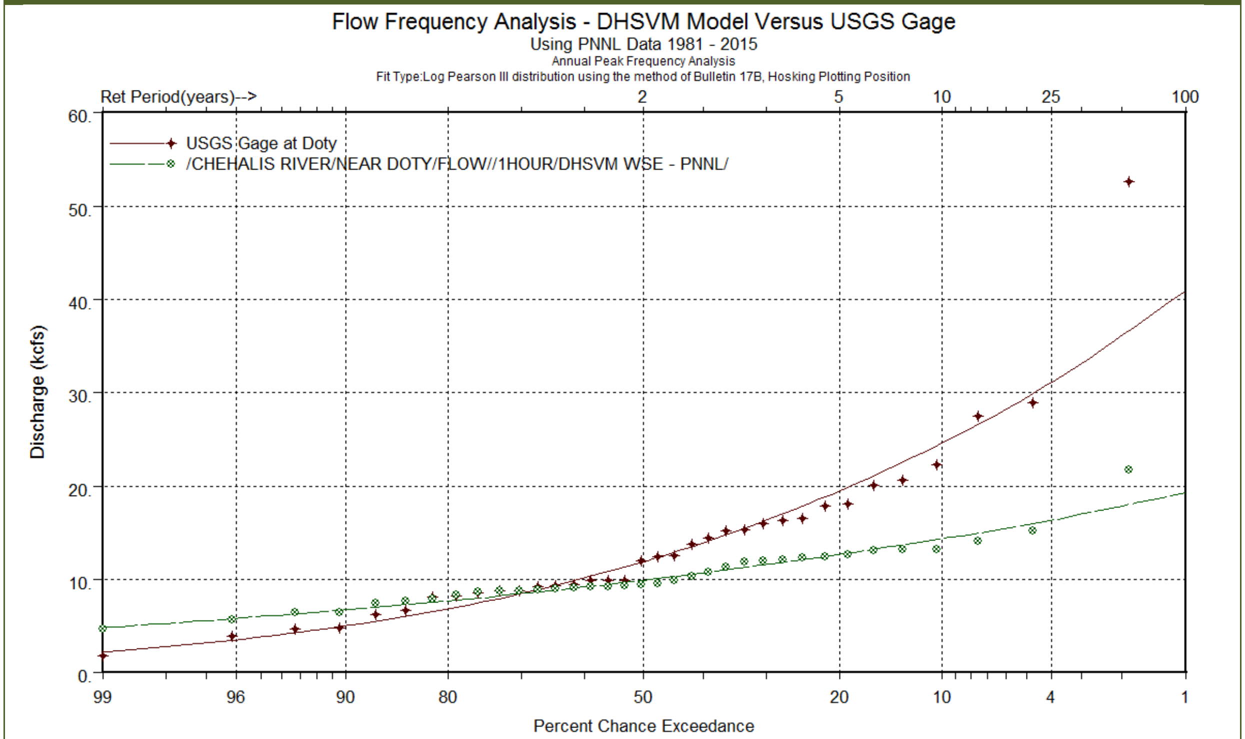


Figure 10
Frequency Curve for Peak Annual Flows on Newaukum River at Chehalis

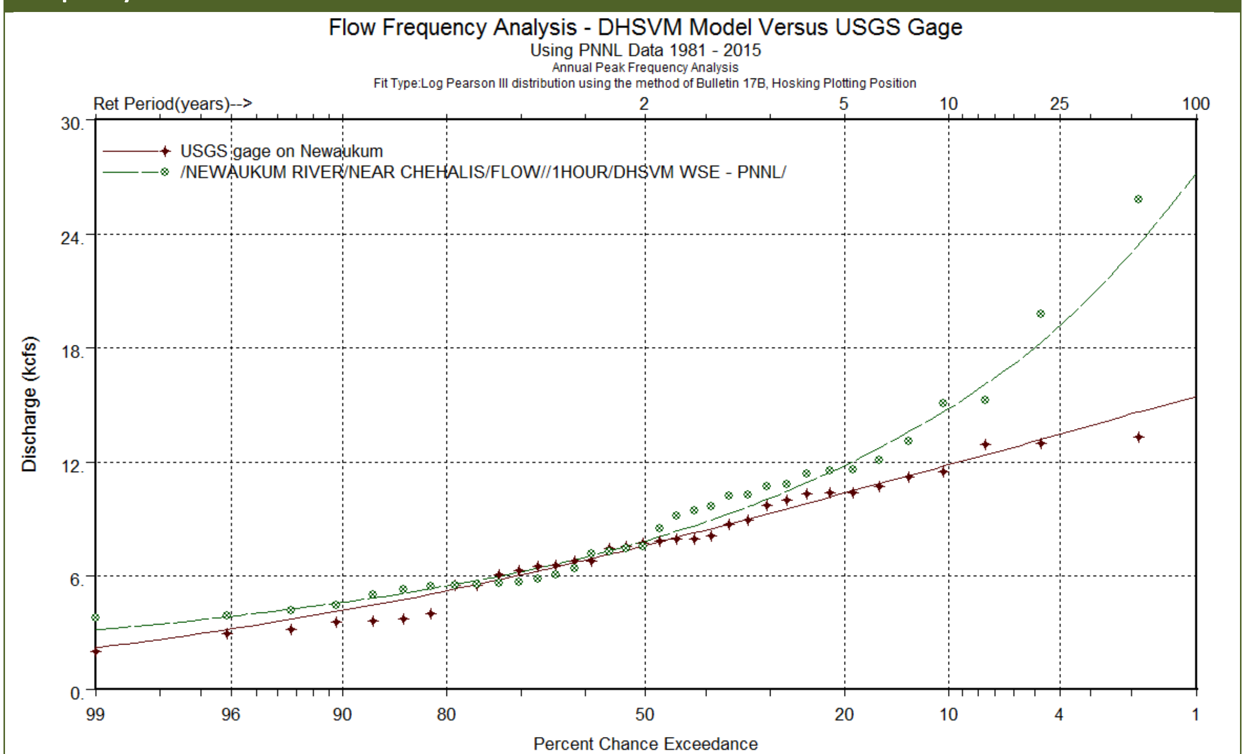


Figure 11
Frequency Curve for Peak Annual Flows on Satsop River at Satsop

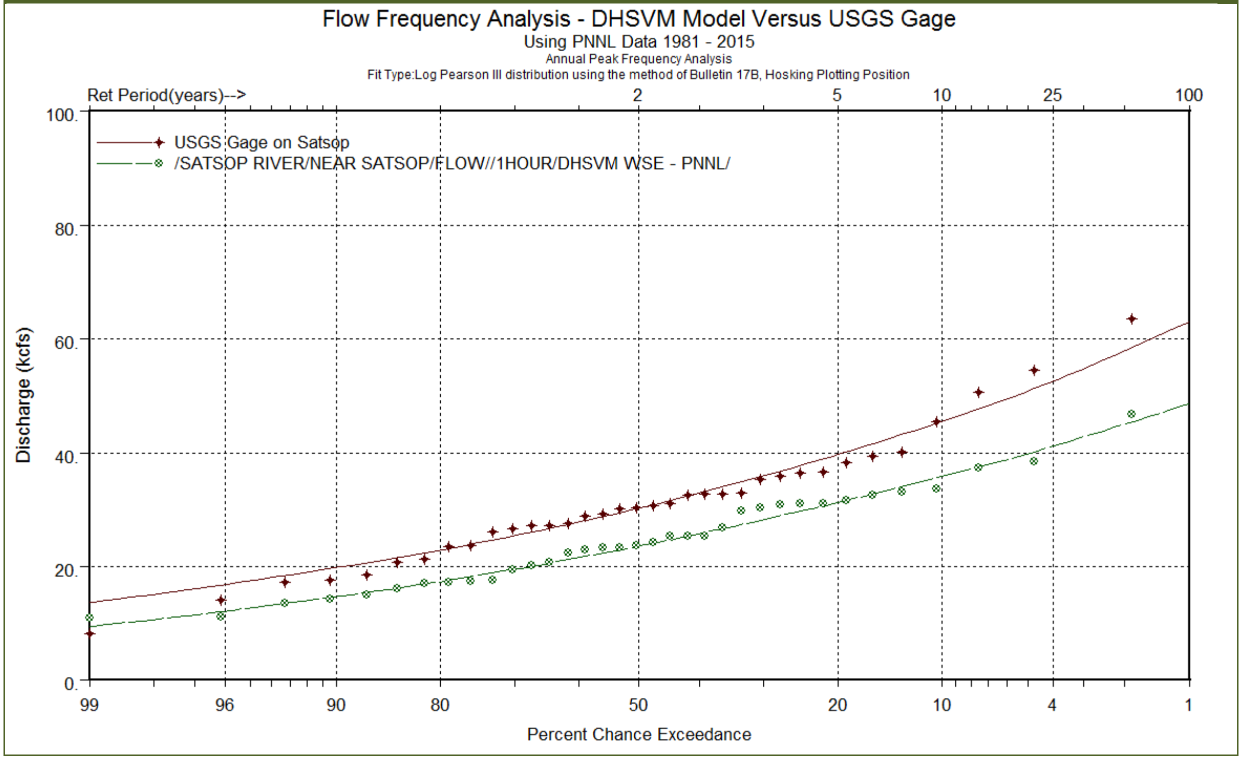


Figure 12
Frequency Curve for Peak Annual Flows on Chehalis River at Grand Mound

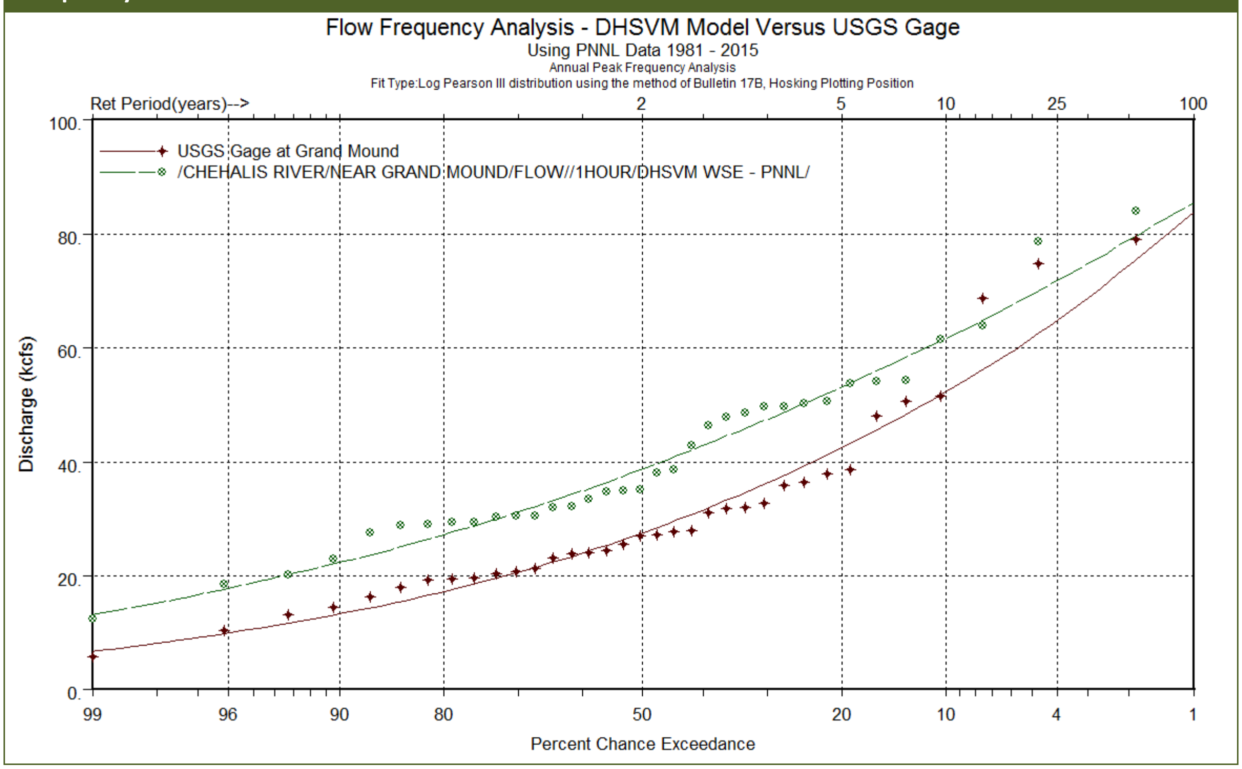
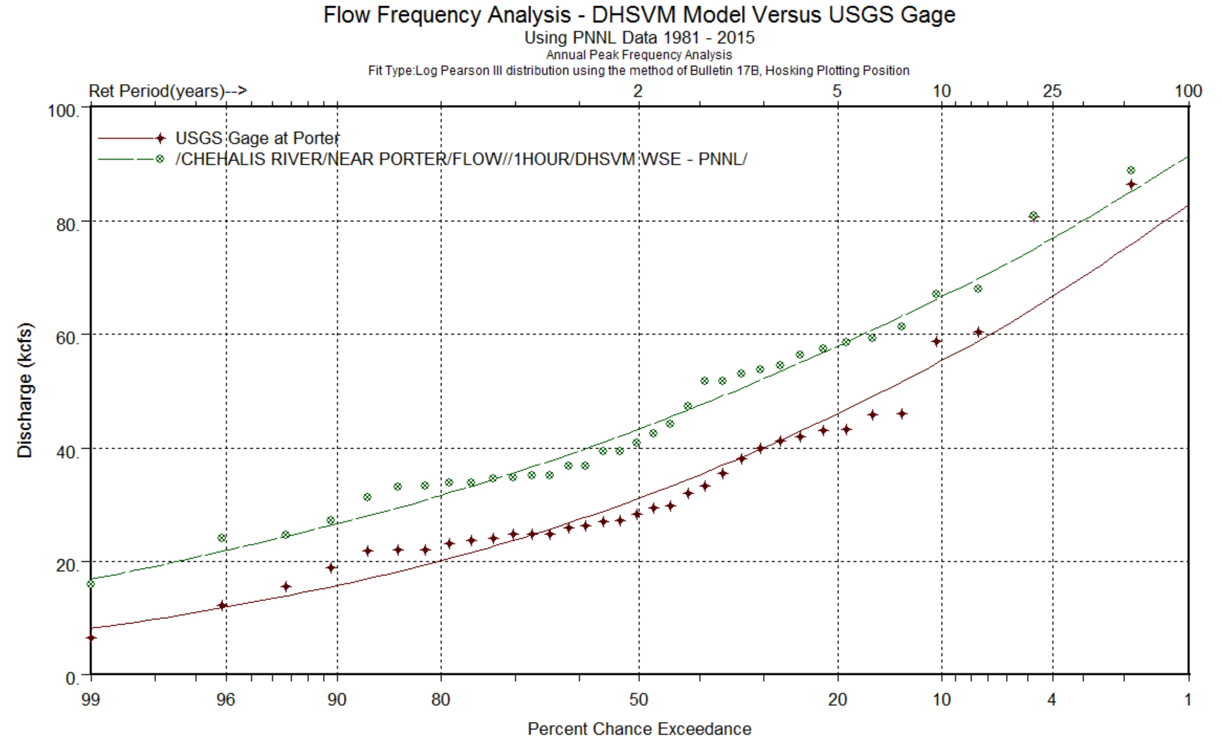


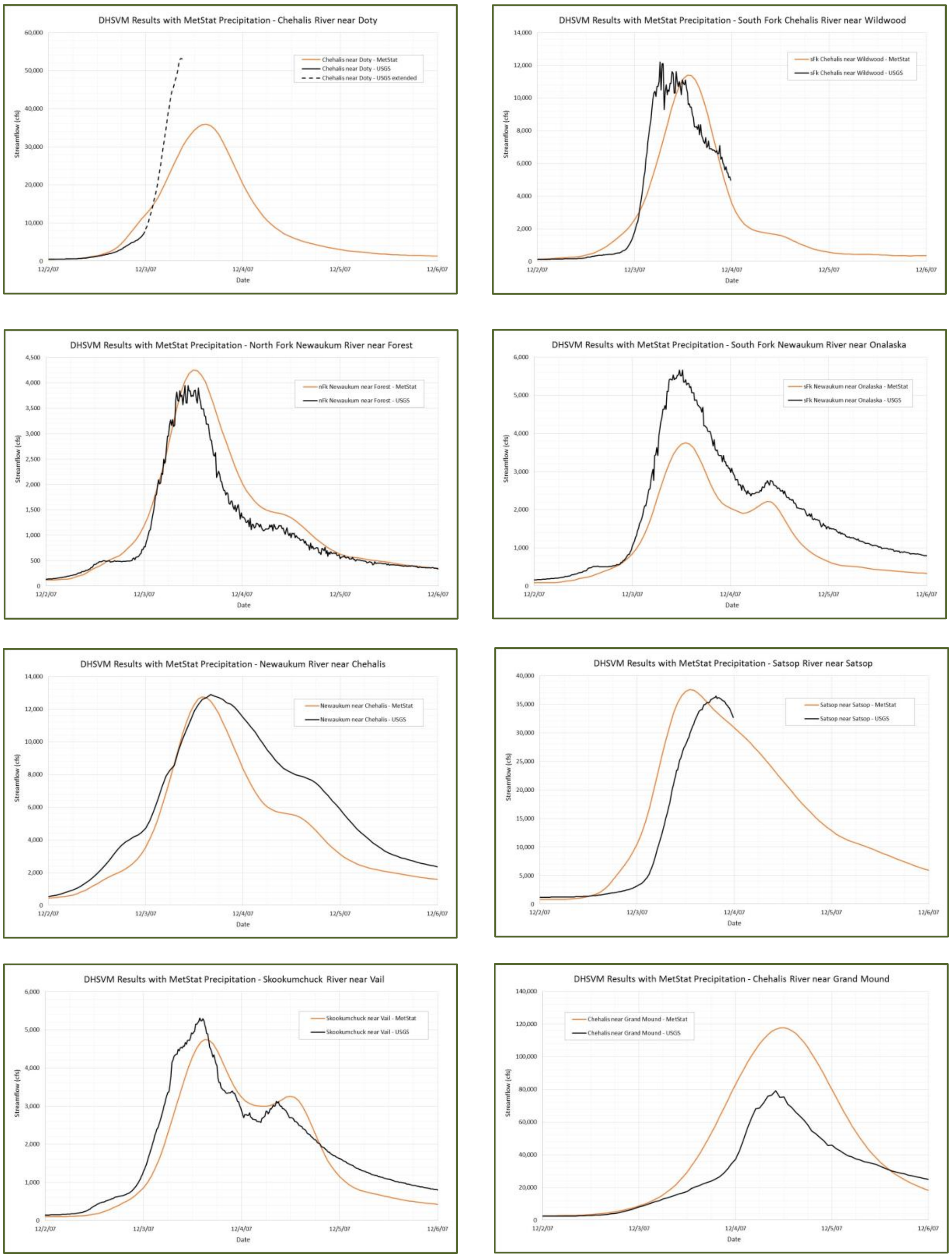
Figure 13
Frequency Curve for Peak Annual Flows on Chehalis River at Porter



Simulation of December 2007 Flood Event

As discussed previously, the PNNL data often under- or overestimate precipitation totals for individual storm events. Specifically, the PNNL data for the December 2007 event seems to dramatically underestimate the precipitation that actually occurred in much of the basin. A test run of the DHSVM model was made to evaluate the performance of the model using the more accurate MetStat precipitation data. Hourly PNNL precipitation data for the December 3-7 period were replaced in the dataset with MetStat data and the model was rerun for this event. Results of these simulations at eight locations are shown in Figure 14. As shown in Figure 14, simulations using the more accurate precipitation data generally agree quite well with USGS streamflow observations. Exceptions to this are the South Fork Newaukum near Onalaska, where the simulated flow is significantly lower than the observed value and the Chehalis River near Grand Mound gage where the simulated peak is significantly higher than the observed value. While the cause of these simulation errors is unclear, we surmise that the precipitation data for the SF Newaukum site might still be underrepresenting what actually occurred in that basin. For the Grand Mound location one issue that may contribute to the oversimulation is the fact that DHSVM uses kinematic wave channel routing and thus ignores backwater effects, potentially leading to oversimulation during floods where there is a lot of overbank flood storage. Despite the results at these two locations the hydrographs shown in Figure 14 generally support the conclusion that the DHSVM model performs reasonably well if accurate precipitation data are used.

Figure 14
Simulations of December 2007 Flood Event Using MetStat Precipitation data



6.0 Discussion of Results and Model Application

As documented in Tables 5 and 6 and Figures 8 through 14, the DHSVM model simulates Chehalis basin hydrology reasonably well, particularly when accurate precipitation data are available to drive the simulations. Figures 8 and 14 show good mimicry of flow hydrographs, for a broad range of flood events and for periods between events. Figures 9 through 13 and Table 6 show that the model does a good job of replicating flow frequency results at some locations and recurrence intervals, although it does poorly at other locations. Overall there does not appear to be a universal trend towards overestimation or underestimation of runoff volumes or peak flows. The following observations can be made based on the calibration comparisons:

- **Mean Annual Flow:** Mean annual flows at the 5 calibration locations are generally simulated to within ±10% with the exception of the Satsop gage, which is likely a function of precipitation bias in the lower basin, and the Doty gage, which is highly affected by poor simulation of the December 2007 flood event.
- **Nash-Sutcliffe Efficiency:** NSE for the final calibration runs in the three MOCOM basins (Doty, Newaukum, and Satsop) range from 0.80 to 0.84. A value of 1.0 denotes perfect calibration and values above 0.7 are generally considered to indicate decent model calibration.
- **Doty Flood Frequency**: Unscaled PNNL based simulations match flow quantiles well up to 2-year event. Low frequency events are under-simulated by about 50%.
- **Newaukum Flood Frequency**: Unscaled PNNL based simulations match flow quantiles well up to 2-year event. Low frequency events are over-simulated by about 50%.
- **Satsop Flood Frequency**: Unscaled PNNL based simulations too low by about 25% across the board (probably due to low bias in PNNL precipitation in the lower Chehalis basin).
- **Grand Mound Flood Frequency**: Unscaled PNNL based simulations are roughly 20% too high up to the 10-year event, then match reasonably well for low frequency events.
- **Porter Flood Frequency**: Unscaled PNNL based simulations are roughly 20% too high up to the 10-year event, then match reasonably well for low frequency events.

Table 7 shows the peak simulated flows for the 1981 – 2015 simulation period for each of the five calibration sites and compares these to the corresponding USGS observed peak discharges. The discharges are ranked from highest to lowest (based on the observed peak) and the error associated with each simulated discharge is reported. The average of the 10 highest discharges is also computed and listed in the header row (for purposes of this report these events are termed “extreme floods”).

For the Newaukum River near Chehalis, the Chehalis River near Grand Mound, and the Chehalis River near Porter, the average error in peak flows for extreme events is fairly small at less than 15%. For the Satsop River near Satsop gage, the average error for extreme floods (and actually all floods) is approximately negative 29%, which is thought to be the reflection of a negative rainfall bias in the PNNL data for that part of the watershed (see Figure 7 and Mauger et al, 2018). For the Doty gage there is a strong negative bias in the simulations of peak flows (-46%). It is not clear whether this is the result of precipitation biases, shortcomings in the calibration, or some other cause. While the reason for the under-simulation of extreme floods in the Doty basin has not been determined, none of the sensitivity analyses described in Section 5 identified any alternative DHSVM model parameters that would significantly improve the calibration results at that location. It is possible that the results at the Doty gage reflect a low bias in the rainfall data for extreme flood events. The errors may also be due to the shallow bedrock underlying much of the upper Chehalis basin or other soil or channel characteristics that DHSVM is not able to fully represent. Future calibration efforts focusing on different combinations of soils thickness, soil properties, and channel characteristics in this basin might achieve a better calibration, but the available data and schedule for this project did not allow additional calibration efforts.

As noted previously, the PNNL meteorological data used as input to the hydrologic model may be generally biased low and may not accurately match some historical storms in the basin (see Section 4). For example, the storm of November 1986 was only the fourth to seventh largest observed event at the Newaukum and lower Chehalis River gages and yet was by far the largest simulated event in the DHSVM model at those locations. On the other hand, the February 1996 flood was the second or third largest event ever observed at gages throughout the basin but was a rather small event in the DHSVM simulations due to very low rainfall in the PNNL dataset. Despite potential issues such as these, the PNNL dataset is the best available source of basin-wide, short interval, historical meteorological data, and the DHSVM model developed for this study provides a reasonable tool for evaluating potential changes in basin hydrology due to climate change.

While the simulation results for peak flows are generally considered fair, one finding of this study was that DHSVM is difficult to calibrate to extreme floods, especially at locations with significant floodplain storage. This result is common to many hydrologic models as most of these use approximate channel routing techniques (kinematic wave routing, level pool routing, etc.) or don’t include channel routing at all (e.g. VELMA). Many past studies have avoided this issue by focusing on calibration to gages located on steeper headwater streams with limited floodplain storage (Lundquist, 2019). In the Chehalis River Basin, however, there are no long term streamflow gages located in the headwaters and as such there was insufficient data to calibrate the model to flood frequency curves in steeper channels. In theory it would be possible to link the DHSVM runoff from all streams with a hydraulic routing model (such as the RiverFlow2D hydraulic model recently prepared by WSE (2019)), but this would take significant time and resources beyond the scope of the current study. Future efforts to improve the hydrologic model calibration could evaluate the benefits of linking DHSVM with a detailed hydraulic routing model for calibration to locations on major rivers.

Table 7

Simulated and Observed Peak Annual Flows

Chehalis River Near Doty

Year	Observed Flow Peak (cfs)	Observed Flow Date	Simulated Flow Peak (cfs)	Simulated Flow Date	Time	Error Ave %
						-46%
2008	53500	3-Dec-07	21714	3-Dec-07	13:00	-59%
1996	28900	8-Feb-96	10366	6-Feb-96	23:00	-64%
1990	27500	9-Jan-90	9357	28-Jan-90	17:00	-66%
2013	22300	19-Nov-12	8995	4-Dec-12	9:00	-60%
1991	20600	24-Nov-90	9625	4-Feb-91	20:00	-53%
2009	20100	8-Jan-09	13253	8-Jan-09	3:00	-34%
1986	18100	18-Jan-86	7499	18-Jan-86	18:00	-59%
1987	17900	24-Nov-86	15175	3-Mar-87	17:00	-15%
2002	16600	16-Dec-01	12090	16-Dec-01	17:00	-27%
1999	16300	24-Feb-99	13115	24-Feb-99	10:00	-20%
2006	16000	30-Jan-06	11352	30-Jan-06	11:00	-29%
1995	15300	20-Dec-94	12340	18-Dec-94	2:00	-19%
1983	15200	3-Dec-82	13237	3-Dec-82	21:00	-13%
2007	14500	6-Nov-06	12403	7-Nov-06	4:00	-14%
1988	13800	9-Dec-87	8896	14-Jan-88	17:00	-36%
1997	12600	19-Mar-97	12622	1-Jan-97	4:00	0%
2000	12400	15-Dec-99	11921	15-Dec-99	19:00	-4%
1981	12000	26-Dec-80	9437	19-Feb-81	9:00	-21%
1998	9920	30-Oct-97	9256	23-Jan-98	13:00	-7%
2011	9910	12-Dec-10	9235	12-Dec-10	16:00	-7%
2012	9880	23-Nov-11	12062	29-Mar-12	22:00	22%
2010	9460	17-Nov-09	8832	19-Nov-09	15:00	-7%
2014	9350	17-Feb-14	6488	9-Mar-14	6:00	-31%
2005	9270	11-Dec-04	7721	18-Jan-05	1:00	-17%
1992	8770	28-Jan-92	9142	31-Jan-92	9:00	4%
2015	8770	6-Feb-15	6452	6-Feb-15	9:00	-26%
1982	8600	24-Jan-82	14125	23-Jan-82	23:00	64%
2004	8270	21-Oct-03	8795	19-Nov-03	2:00	6%
2003	8150	31-Jan-03	7860	16-Dec-02	8:00	-4%
1994	6720	10-Dec-93	10840	10-Dec-93	10:00	61%
1989	6250	30-Dec-88	8327	30-Dec-88	9:00	33%
1984	4790	15-Nov-83	8640	15-Nov-83	5:00	80%
1985	4750	2-Nov-84	9892	2-Nov-84	8:00	108%
1993	3880	25-Jan-93	5664	23-Mar-93	4:00	46%
2001	1830	16-Dec-00	4729	22-Dec-00	8:00	158%
Average	13776		10327			-25%
Median	12000		9437			-21%

Newaukum River Near Chehalis

Year	Observed Flow Peak (cfs)	Observed Flow Date	Simulated Flow Peak (cfs)	Simulated Flow Date	Time	Error Ave %
						7%
1996	13300	8-Feb-96	7553	11-Nov-95	13:00	-43%
2009	13000	7-Jan-09	11573	7-Jan-09	21:00	-11%
2008	12900	3-Dec-07	19770	3-Dec-07	17:00	53%
2015	11500	5-Jan-15	5834	5-Jan-15	10:00	-49%
2007	11200	7-Nov-06	13098	7-Nov-06	11:00	17%
1987	10700	24-Nov-86	25801	24-Nov-86	5:00	141%
1990	10400	9-Jan-90	6368	9-Jan-90	23:00	-39%
1991	10300	24-Nov-90	9144	24-Nov-90	21:00	-11%
1999	10000	26-Nov-98	10708	26-Nov-98	3:00	7%
1997	9700	29-Dec-96	10222	1-Jan-97	8:00	5%
2003	8940	31-Jan-03	5476	2-Jan-03	21:00	-39%
2006	8720	30-Jan-06	12080	30-Jan-06	13:00	39%
2000	8100	16-Dec-99	15095	15-Dec-99	22:00	86%
1986	7960	23-Feb-86	11517	18-Jan-86	22:00	45%
2002	7920	17-Dec-01	10843	8-Jan-02	2:00	37%
1983	7820	4-Dec-82	9670	4-Dec-82	0:00	24%
2005	7740	18-Jan-05	6077	18-Jan-05	10:00	-21%
2013	7560	20-Nov-12	5533	29-Sep-13	5:00	-27%
2004	7460	30-Jan-04	8520	19-Nov-03	8:00	14%
2014	6780	17-Feb-14	4170	9-Mar-14	10:00	-38%
1984	6760	25-Jan-84	9424	25-Jan-84	7:00	39%
1998	6580	14-Jan-98	3902	23-Jan-98	16:00	-41%
2011	6500	16-Jan-11	10254	16-Jan-11	14:00	58%
2012	6300	22-Feb-12	7269	23-Nov-11	8:00	15%
1995	6040	27-Dec-94	11352	19-Feb-95	18:00	88%
1988	5500	10-Dec-87	5276	26-Mar-88	9:00	-4%
1981	5490	26-Dec-80	7154	16-Feb-81	10:00	30%
1992	3990	28-Jan-92	5700	31-Jan-92	5:00	43%
1993	3730	11-Apr-93	5563	25-Jan-93	21:00	49%
1985	3630	4-Nov-84	5596	27-Nov-84	0:00	54%
1989	3570	30-Dec-88	4465	22-Nov-88	18:00	25%
1994	3170	5-Jan-94	7466	10-Dec-93	22:00	136%
2010	2940	19-Nov-09	4993	20-Dec-09	15:00	70%
2001	2030	11-Apr-01	3809	19-Mar-01	4:00	88%
1982			15230	24-Jan-82	0:00	
Average	7595		9043			19%
Median	7650		7553			-1%

Satsop River Near Satsop

Year	Observed Flow Peak (cfs)	Observed Flow Date	Simulated Flow Peak (cfs)	Simulated Flow Date	Time	Error Ave %
						-29%
1997	63600	19-Mar-97	29706	19-Jan-97	6:00	-53%
2000	54500	15-Dec-99	31699	15-Dec-99	17:00	-42%
1995	50600	20-Dec-94	30989	19-Feb-95	22:00	-39%
2009	45500	7-Jan-09	46747	8-Jan-09	0:00	3%
2007	40100	7-Nov-06	37274	7-Nov-06	5:00	-7%
1987	39300	23-Nov-86	32494	4-Mar-87	3:00	-17%
1991	38200	24-Nov-90	23047	24-Nov-90	19:00	-40%
2011	36700	12-Dec-10	25281	16-Jan-11	12:00	-31%
2008	36400	3-Dec-07	22448	4-Dec-07	5:00	-38%
2004	35900	21-Oct-03	25379	18-Nov-03	23:00	-29%
1999	35400	29-Dec-98	30397	13-Nov-98	22:00	-14%
1994	33000	10-Dec-93	20839	2-Mar-94	15:00	-37%
1983	32800	4-Dec-82	33676	3-Dec-82	20:00	3%
1984	32800	15-Nov-83	23310	16-Nov-83	1:00	-29%
1981	32600	16-Feb-81	31131	16-Feb-81	10:00	-5%
1982	31000	14-Feb-82	38483	23-Jan-82	21:00	24%
1996	30800	29-Nov-95	31160	11-Dec-95	3:00	1%
1986	30300	18-Jan-86	19462	24-Feb-86	8:00	-36%
2002	30100	17-Dec-01	25429	22-Feb-02	9:00	-16%
2005	29200	18-Jan-05	33102	18-Jan-05	10:00	13%
2013	28900	19-Nov-12	17459	19-Nov-12	20:00	-40%
2010	27600	20-Nov-09	23272	12-Jan-10	9:00	-16%
1990	27300	10-Feb-90	16053	5-Dec-89	4:00	-41%
1998	27200	30-Oct-97	23676	23-Jan-98	16:00	-13%
2006	26600	30-Jan-06	13636	30-Jan-06	9:00	-49%
2015	26100	5-Jan-15	17665	5-Jan-15	7:00	-32%
1992	23700	20-Nov-91	26891	31-Jan-92	9:00	13%
1993	23500	25-Jan-93	15098	25-Jan-93	17:00	-36%
2014	21400	9-Mar-14	11031	9-Mar-14	4:00	-48%
1988	20800	10-Dec-87	14209	6-Apr-88	8:00	-32%
2003	18600	2-Jan-03	20277	14-Mar-03	1:00	9%
1989	17600	5-Apr-89	17289	30-Dec-88	7:00	-2%
2012	17200	29-Dec-11	24209	23-Nov-11	10:00	41%
1985	14200	14-Dec-84	17103	2-Nov-84	15:00	20%
2001	8190	5-Jan-01	11138	5-Jan-01	7:00	36%
Average	31077		24602			-21%
Median	30300		23676			-22%

Chehalis River near Grand Mound

Year	Observed Flow Peak (cfs)	Observed Flow Date	Simulated Flow Peak (cfs)	Simulated Flow Date	Time	Error Ave %
						8%
2008	79100	4-Dec-07	78767	4-Dec-07	10:00	0%
1996	74800	9-Feb-96	34738	7-Feb-96	21:00	-54%
1990	68700	10-Jan-90	29437	29-Jan-90	19:00	-57%
1987	51600	25-Nov-86	83996	24-Nov-86	20:00	63%
2009	50700	8-Jan-09	61565	8-Jan-09	19:00	21%
1991	48000	25-Nov-90	38706	25-Nov-90	15:00	-19%
1997	38700	30-Dec-96	49792	2-Jan-97	0:00	29%
2006	37900	31-Jan-06	50558	31-Jan-06	6:00	33%
1999	36500	26-Nov-98	47819	25-Feb-99	9:00	31%
1995	35900	21-Dec-94	46337	20-Feb-95	10:00	29%
2007	32700	8-Nov-06	54328	8-Nov-06	2:00	66%
1986	32100	20-Jan-86	38172	19-Jan-86	14:00	19%
2002	31900	18-Dec-01	49763	17-Dec-01	15:00	56%
2000	31000	17-Dec-99	53739	16-Dec-99	13:00	73%
2015	28000	6-Jan-15	18596	19-Jan-15	3:00	-34%
2014	27800	18-Feb-14	20125	10-Mar-14	5:00	-28%
1982	27300	25-Jan-82	63881	24-Jan-82	18:00	134%
2013	27000	21-Nov-12	29099	20-Nov-12	19:00	8%
1983	25600	5-Dec-82	48679	4-Dec-82	16:00	90%
2012	24500	16-Mar-12	54182	24-Nov-11	2:00	121%
1981	24000	27-Dec-80	33440	20-Feb-81	9:00	39%
2011	23900	17-Jan-11	35078	13-Dec-10	13:00	47%
2003	23100	1-Feb-03	29389	3-Jan-03	14:00	27%
1998	21400	15-Jan-98	28945	24-Jan-98	16:00	35%
2005	20700	19-Jan-05	30586	19-Jan-05	2:00	48%
2004	20400	31-Jan-04	42871	19-Nov-03	21:00	110%
1992	19600	30-Jan-92	30414	29-Jan-92	4:00	55%
2010	19400	18-Nov-09	32170	20-Nov-09	16:00	66%
1984	19200	26-Jan-84	35016	25-Jan-84	23:00	82%
1985	18000	29-Nov-84	30617	28-Nov-84	20:00	70%
1988	16400	11-Dec-87	32078	15-Jan-88	17:00	96%
1989	14400	31-Dec-88	27569	31-Dec-88	9:00	91%
1994	13100	4-Mar-94	50273	11-Dec-93	10:00	284%
1993	10400	12-Apr-93	22897	26-Jan-93	15:00	120%
2001	5750	5-Feb-01	12521	23-Dec-00	12:00	118%
Average	30844		40747			32%
Median	27000		35078			30%

Chehalis River Near Porter

Year	Observed Flow Peak (cfs)	Observed Flow Date	Simulated Flow Peak (cfs)	Simulated Flow Date	Time	Error Ave %
						13%
2008	86500	5-Dec-07	80857	5-Dec-07	5:00	-7%
1996	80700	9-Feb-96	44214	8-Feb-96	17:00	-45%
1990	60400	11-Jan-90	34826	30-Jan-90	15:00	-42%
2009	58700	9-Jan-09	67136	9-Jan-09	13:00	14%
1997	46000	2-Jan-97	61388	2-Jan-97	4:00	33%
1987	45900	25-Nov-86	88794	25-Nov-86	15:00	93%
2006	43200	13-Jan-06	56300	1-Feb-06	2:00	30%
1991	43000	26-Nov-90	42556	26-Nov-90	9:00	-1%
1999	42000	26-Feb-99	52998	22-Nov-98	17:00	26%
2002	41200	19-Dec-01	53753	18-Dec-01	10:00	30%
2000	38100	17-Dec-99	58565	17-Dec-99	7:00	54%
1995	35600	22-Dec-94	51775	21-Feb-95	4:00	45%
1982	33300	26-Jan-82	68051	25-Jan-82	12:00	104%
1981	32000	28-Dec-80	36745	17-Feb-81	23:00	15%
2014	29800	19-Feb-14	24566	1-Oct-13	1:00	-18%
2007	29400	9-Nov-06	57517	8-Nov-06	21:00	96%
2015	28300	7-Jan-15	23997	8-Feb-15	6:00	-15%
2013	27300	21-Nov-12	34574	21-Nov-12	16:00	27%
2011	27000	15-Dec-10	39389	14-Dec-10	9:00	46%
2012	26200	17-Mar-12	59301	24-Nov-11	21:00	126%
2003	26000	2-Feb-03	33936	4-Jan-03	11:00	31%
1992	24900	31-Jan-92	33108	1-Feb-92	23:00	33%
2004	24900	1-Feb-04	47329	20-Nov-03	16:00	90%
1983	24800	8-Jan-83	51756	5-Dec-82	11:00	109%
1998	24100	17-Jan-98	33769	25-Jan-98	11:00	40%
2010	23800	19-Nov-09	36725	21-Nov-09	11:00	54%
1984	23200	26-Jan-84	39478	26-Jan-84	16:00	70%
2005	22100	20-Jan-05	33325	19-Jan-05	21:00	51%
1988	22000	17-Jan-88	35221	16-Jan-88	12:00	60%
1985	21800	30-Nov-84	35158	29-Nov-84	16:00	61%
1989	18900	1-Jan-89	31349	1-Jan-89	3:00	66%
1994	15500	5-Mar-94	54611	12-Dec-93	5:00	252%
1993	12300	27-Jan-93	27193	27-Jan-93	9:00	121%
2001	6550	5-Feb-01	15905	24-Dec-00	7:00	143%
1986			40911	25-Feb-86	14:00	
Average	33690		45345			35%
Median	27800		40911			47%

Climate Change Simulations

To simulate the effect of climate change on Chehalis Basin hydrology, the DHSVM model was set up and run using the two long-term GCM based meteorological data sets described in Section 4. These two data sets are intended to represent a wide range of future meteorological and hydrologic conditions, with ACCESS 1.0 RCP 4.5 representing a low-end estimate of future climate conditions and the GFDL CM3 RCP 8.5 data representing a high-end estimate of future climate conditions.

The calibrated DHSVM model of the Chehalis River Basin was run for the full period of meteorological record (1970 – 2099). Hourly simulated flows were extracted at 15 locations across the basin including the five gage locations used for model calibration. These hourly simulated flow data were stored in a HEC-DSS database file and peak annual flows were extracted for each year in the simulated record. The data were subdivided into three 45-year periods as follows: 1970 – 2015 (current), 2016 – 2060 (mid-century), and 2055 – 2099 (late century). Frequency analyses were then conducted on the peak flows for the three periods for five locations (the same sites as used in the calibration except a location at the mouth of the Chehalis River was substituted for the Porter gage). The results of the frequency analysis are summarized in Table 8 with full results and flow frequency plots included in Appendix Band a discussion of these latest results and previous climate change predictions is provided in Appendix C.

Table 8

Flood Frequency Analysis Results for Climate Change Simulations

Estimate Average Increase in Chehalis Basin Flows Due to Climate Change			
ACCESS 1.0 RCP 4.5 - Instantaneous Peak Flow Increases			
Average (mid century 15 sites) =	13%	Average (late century 15 sites) =	11%
Minimum (mid century 15 sites) =	2%	Minimum (late century 15 sites) =	0%
Maximum (mid century 15 sites) =	22%	Maximum (late century 15 sites) =	23%
ACCESS 1.0 RCP 4.5 - 3-Day Duration Flow Increases			
Average (mid century 15 sites) =	12%	Average (late century 15 sites) =	15%
Minimum (mid century 15 sites) =	-4%	Minimum (late century 15 sites) =	1%
Maximum (mid century 15 sites) =	24%	Maximum (late century 15 sites) =	29%
GFDL CM3 RCP 8.5 - Instantaneous Peak Flow Increases			
Average (mid century 15 sites) =	11%	Average (late century 15 sites) =	26%
Minimum (mid century 15 sites) =	-1%	Minimum (late century 15 sites) =	14%
Maximum (mid century 15 sites) =	31%	Maximum (late century 15 sites) =	47%
GFDL CM3 RCP 8.5 - 3-Day Duration Flow Increases			
Average (mid century 15 sites) =	17%	Average (late century 15 sites) =	28%
Minimum (mid century 15 sites) =	7%	Minimum (late century 15 sites) =	16%
Maximum (mid century 15 sites) =	32%	Maximum (late century 15 sites) =	44%
GFDL CM3 RCP 8.5 - 7-Day Duration Flow Increases			
Average (mid century 15 sites) =	13%	Average (late century 15 sites) =	17%
Minimum (mid century 15 sites) =	7%	Minimum (late century 15 sites) =	10%
Maximum (mid century 15 sites) =	25%	Maximum (late century 15 sites) =	23%

As shown in Table 8, the analysis indicates that flow frequency quantiles will increase under either future climate change scenario. For the ACCESS 1.0 RCP 4.5 (low end) scenario average peak flows are predicted to change by 13% at mid-century and by 11% by the late century[2]. Instantaneous peak flows under the GFDL CM3 RCP 8.5 (high end) scenario are projected to change by 11% by mid-century and 26% by the late century. Analyses of 3- and 7-day storm volumes showed generally similar results to the peak flow analysis and thus uniform design storm multipliers of 12% increase for mid-century and 26% increase for late century are recommended.

7.0 Summary and Conclusions

This memorandum summarizes WSE's development and calibration of a DHSVM Hydrologic Model of the Chehalis River Basin. The model encompasses approximately 2,700 square miles and includes areas draining to the Chehalis River and those draining directly to Grays Harbor. Physically based input data for the model were derived from various sources including the USGS and NRCS. Meteorological inputs were provided by the UW CIG and include a historical data set covering the period 1981 – 2015 as well as two long term climate simulations covering the period 1970 – 2099. The model was calibrated using the historical data to daily and peak annual data from five USGS streamflow gages in the basin.

The original objective of this project was to develop a tool (e.g. hydrologic model) that could:

1) simulate historical and future hydrology for the basin to provide a robust data set for evaluating potential impacts of climate change
2) generate accurate inputs to hydraulic models of the Chehalis River for both gaged and ungaged areas
3) produce data for use in water quality analyses, sediment transport models, restoration designs, and other studies
4) provide a tool that could be used to produce streamflow forecasts during extreme floods as part of an improved flood warning system

Considering the results of the calibration described in Sections 5 and 6, it is not clear that the current DHSVM model, with the existing PNNL precipitation data, should be used for items 2, 3, and 4. Improved meteorological data, or procedures to refine or adjust the model outputs would be required before the model could be used to support those tasks. In the interim it is recommended that hydraulic modeling and analysis, and other tasks, continue to use the hydrologic data developed in 2014 (USACE, 2014) as the basis for historical simulations.

One task that is felt to be reasonable with the current model is evaluating potential impacts of climate change. Although simulations of individual historical floods at specific locations appear to be subject to

[2] Considering all of the uncertainties in the modeling and analysis the changes projected for the RCP4.5 scenario at mid and late century, as well as the changes projected for the RCP 8.5 scenario at mid-century are considered to be the same.

considerable error, the climate change evaluation uses simulations of current (1970 – 2015) and future (2016 – 2060 and 2055 – 2099) periods, and the evaluation is based on the relative change in flows (percentage increase or decrease) as opposed to the absolute magnitude of any particular event or change. As discussed in Section 6, the simulation results indicate that future flows may increase by an average of 12 to 26% as a result of the projected effects of climate change on meteorological conditions. Note that the predicted changes in flows at individual locations for specific recurrence intervals range from a decrease of 1% to an increase of more than 47%. However given the nuances of flood frequency analysis and the uncertainties inherent in the meteorological data and hydrologic modeling for this study, it is suggested that use of the average change is more appropriate than any single point of comparison. A comparison between the current climate change predictions and previous studies is provided in Appendix C (Mauger, 2019).

Calibrating a hydrologic model to a basin the size and complexity of the Chehalis River Basin is an ambitious task. In particular, obtaining a reliable historical short-interval meteorological data set spanning many years is problematic, if not impossible. Additionally, defining model parameters such as soil properties and channel characteristics that adequately represent the complexities in the basin involves extensive trial and error testing, all of which takes considerable time and effort. Given these challenges, the model developed for this study is considered to be a good first step towards creating a tool that can meet all the objectives previously described. The model matches observed flows well in cases where the precipitation data are considered accurate, particularly in locations where channel and floodplain routing are not significant.

Listed below are recommendations for future work, outside the scope of the current study, which could be undertaken to improve the quality and applicability of the DHSVM model:

- Obtain more accurate meteorological data. It is believed that improvements to the meteorological data would improve the overall performance of the DHSVM model. Researchers at the UW CIG are currently seeking funding to enhance the PNNL data set by integrating gage observations with the modeled downscaled data to more accurately represent storm intensities and spatial distributions in the data. In the future, if improved meteorological data become available the DHSVM model calibration could be revisited and enhanced.
- Obtain paired, spatially-distributed rainfall data and streamflow gaging for headwater areas (such as those proposed for study of forest practices by DNR). This would allow more detailed calibration of soil parameters in locations where channel and floodplain storage are not significant.
- Link the DHSVM model with a hydraulic model of the stream channel to simulate channel and floodplain routing in extreme floods. Use this linked model to improve the model calibration at locations with significant floodplain storage effects.
- Simulate additional global climate model data sets to improve predictions of potential climate change effects. Researchers at the UW CIG are currently working to dynamically downscale

addition GCM simulations. Evaluation of a minimum of six GCMs is typically considered necessary to instill confidence in climate change predictions (Mauger et al, 2018).

- Test using the DHSVM model with National Weather Service precipitation forecasts or real-time NEXRAD data to see if basin-wide flow forecasts can be improved for use in the NWS River Forecast Center flood forecasting.

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APPENDIX A – DHSVM SOIL TYPES WITH CORRESPONDING SOIL PARAMETERS

INITIAL PARAMETERS	SOIL DESCRIPTION	LATERAL CONDUCTIVITY	EXPONENTIAL DECREASE	MAXIMUM INFILTRATION	DEPTH THRESHOLD	CAPILLARY DRIVE	SURFACE ALBEDO	NUMBER OF SOIL LAYERS	POROSITY	PORE SIZE DISTRIBUTION	BUBBLING PRESSURE	FIELD CAPACITY	WILTING POINT	BULK DENSITY	VERTICAL CONDUCTIVITY	THERMAL CONDUCTIVITY	THERMAL CAPACITY
CALIBRATED	(TXT)	(M/S)	(CONST)	(M/S)	(M)	-	(M/S)	(CONST)	(%)	(INDEX)	-	(%)	(%)	(KG/M^3)	(M/S)	(W/(M*DEGC))	(J/(M^3*DEGC))
Soil 1	SAND	0.01	3.0	0.00020	0.5	0.1	0.1	3	0.43	0.24	0.07	0.08	0.03	1492	0.01	7.114 6.923 6.923	1400000
Soil 2	LOAMY SAND	0.01	3.0	0.00006	0.5	0.1	0.1	3	0.42	0.25	0.09	0.15	0.06	1520	0.01	7.114 6.923 7.0	1400000
Soil 3	SANDY LOAM	0.01	3.0	0.00003	0.5	0.1	0.1	3	0.40	0.21	0.15	0.21	0.09	1569	0.01	7.114 6.923 7.0	1400000
Soil 4	SILTY LOAM	0.015	3.0	0.00003	0.5	0.1	0.1	3	0.46	0.26	0.21	0.32	0.12	1419	0.01	7.114 6.923 7.0	1400000
		0.005	4.9	0.00025													
Soil 5	SILT	0.01	3.0	0.00003	0.5	0.1	0.1	3	0.52	0.33	0.25	0.28	0.08	1280	0.01	7.114 6.923 7.0	1400000
Soil 6	LOAM	0.00014	0.7	0.00001	0.5	0.1	0.1	3	0.40	0.19	0.11	0.2	0.14	1485	0.0005	7.114 6.923 7.0	1400000
		0.00060	2.4														
Soil 7	SANDY CLAY LOAM	0.01	3.0	0.00001	0.5	0.1	0.1	3	0.39	0.12	0.29	0.27	0.17	1600	0.01	7.114 6.923 7.0	1400000
Soil 8	SILTY CLAY LOAM	0.01	3.0	0.00003	0.5	0.1	0.1	3	0.48	0.13	0.34	0.36	0.21	1381	0.01	7.114 6.923 7.0	1400000
Soil 9	CLAY LOAM	0.01	3.0	0.00001	0.5	0.1	0.1	3	0.46	0.12	0.26	0.31	0.23	1600	0.01	7.114 6.923 7.0	1400000
Soil 10	SANDY CLAY	0.01	3.0	0.00001	0.5	0.1	0.1	3	0.41	0.08	0.29	0.31	0.23	1565	0.01	7.114 6.923 7.0	1400000
Soil 11	SILTY CLAY	0.01	3.0	0.00001	0.5	0.1	0.1	3	0.49	0.1	0.34	0.37	0.25	1346	0.01	7.114 6.923 7.0	1400000
		0.04	4.5	0.00040													
Soil 12	CLAY	0.01	3.0	0.00001	0.5	0.1	0.1	3	0.47	0.08	0.37	0.36	0.27	1394	0.01	7.114 6.923 7.0	1400000
Soil 13	ORGANIC (as loam)	0.01	3.0	0.00001	0.5	0.1	0.1	3	0.43	0.19	0.11	0.29	0.14	1485	0.01	7.114 6.923 7.0	1400000
Soil 14	WATER (as clay)	0.01	3.0	0.00001	0.5	0.1	0.1	3	0.47	0.08	0.37	0.36	0.27	1394	0.01	7.114 6.923 7.0	1400000
Soil 15	BEDROCK	0.01	3.0	0.00001	0.5	0.1	0.1	3	0.10	0.08	0.36	0.05	0.04	1650	0.01	7.114 6.923 7.0	1400000
Soil 16	OTHER (as SCL)	0.01	3.0	0.00001	0.5	0.1	0.1	3	0.39	0.12	0.29	0.27	0.17	1600	0.01	7.114 6.923 7.0	1400000
Soil 17	MUCK	0.01	3.0	0.00001	0.5	0.1	0.23	3	0.47	0.08	0.37	0.36	0.27	1600	0.05	7.114 6.923 7.0	1400000
Soil 18	TALUS	0.01	3.0	0.00020	0.5	0.1	0.1	3	0.80	0.65	0.01	0.03	0.03	1492	0.01	7.114 6.923 6.923	1400000

APPENDIX B –CLIMATE CHANGE SIMULATION RESULTS

Climate Change Summary

Estimated Average Increase in Chehalis Basin Flows Due to Climate Change

ACCESS 1.0 RCP 4.5 - Instantaneous Peak Flow Increases

Average (mid century 15 sites) =	13%	Average (late century 15 sites) =	11%
Minimum (mid century 15 sites) =	2%	Minimum (late century 15 sites) =	0%
Maximum (mid century 15 sites) =	22%	Maximum (late century 15 sites) =	23%

ACCESS 1.0 RCP 4.5 - 3-Day Duration Flow Increases

Average (mid century 15 sites) =	12%	Average (late century 15 sites) =	15%
Minimum (mid century 15 sites) =	-4%	Minimum (late century 15 sites) =	1%
Maximum (mid century 15 sites) =	24%	Maximum (late century 15 sites) =	29%

GFDL CM3 RCP 8.5 - Instantaneous Peak Flow Increases

Average (mid century 15 sites) =	11%	Average (late century 15 sites) =	26%
Minimum (mid century 15 sites) =	-1%	Minimum (late century 15 sites) =	14%
Maximum (mid century 15 sites) =	31%	Maximum (late century 15 sites) =	47%

GFDL CM3 RCP 8.5 - 3-Day Duration Flow Increases

Average (mid century 15 sites) =	17%	Average (late century 15 sites) =	28%
Minimum (mid century 15 sites) =	7%	Minimum (late century 15 sites) =	16%
Maximum (mid century 15 sites) =	32%	Maximum (late century 15 sites) =	44%

GFDL CM3 RCP 8.5 - 7-Day Duration Flow Increases

Average (mid century 15 sites) =	13%	Average (late century 15 sites) =	17%
Minimum (mid century 15 sites) =	7%	Minimum (late century 15 sites) =	10%
Maximum (mid century 15 sites) =	25%	Maximum (late century 15 sites) =	23%

Peaks for Annual Frequency Analysis
DSN1 1040 1H FLOW /CHEHALIS RIVER/AT MOUTH/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN2 6005 1H FLOW /CHEHALIS RIVER/NEAR DOTY/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN3 2427 1H FLOW /CHEHALIS RIVER/NEAR GRAND MOUND/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN4 3168 1H FLOW /NEWAUKUM RIVER/NEAR CHEHALIS/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN5 4608 1H FLOW /SATSOP RIVER/NEAR SATSOP/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/

Average (mid century 15 sites) =	13%	Average (late century 15 sites) =	11%
Minimum (mid century 15 sites) =	2%	Minimum (late century 15 sites) =	0%
Maximum (mid century 15 sites) =	22%	Maximum (late century 15 sites) =	23%

	Return Period	DSN1 3229 1H FLOW /CHEHALIS RIVER/AT MOUTH/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN2 1309 1H FLOW /CHEHALIS RIVER/NEAR DOTY/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN3 6237 1H FLOW /CHEHALIS RIVER/NEAR GRAND MOUND/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN4 6167 1H FLOW /NEWAUKUM RIVER/NEAR CHEHALIS/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN5 920 1H FLOW /SATSOP RIVER/NEAR SATSOP/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change
1970-2015	2	103209		21220		66676		11596		33863	
	5	143890		26666		88589		17270		45691	
	10	171821		29970		102448		21926		53615	
	25	208188		33882		119337		28971		63747	
	50	236043		36637		131528		35156		71388	
	100	264546		39279		143430		42228		79115	
	500	334227		45133		170490		62894		97678	
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2016 - 2060	2	114485	11%	24076	13%	75622	13%	13900	20%	38567	14%
	5	155901	8%	30877	16%	104074	17%	20323	18%	51562	13%
	10	184467	7%	35264	18%	122540	20%	24893	14%	60401	13%
	25	221877	7%	40715	20%	145464	22%	31002	7%	71856	13%
	50	250715	6%	44729	22%	162266	23%	35788	2%	80606	13%
	100	280391	6%	48715	24%	178857	25%	40769	-3%	89548	13%
	500	353669	6%	58034	29%	217198	27%	53260	-15%	111400	14%
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2055 - 2099	2	107493	4%	24063	13%	67102	1%	12780	10%	40970	21%
	5	147189	2%	31657	19%	96877	9%	19358	12%	53023	16%
	10	177092	3%	36537	22%	118812	16%	24383	11%	60674	13%
	25	219224	5%	42572	26%	149092	25%	31518	9%	70054	10%
	50	253930	8%	46991	28%	173544	32%	37422	6%	76871	8%
	100	291619	10%	51357	31%	199649	39%	43847	4%	83568	6%
	500	393027	18%	61475	36%	267889	57%	61137	-3%	98963	1%
Average (2-100)	mid century		8%		19%		20%		9%		13%
Average (2-100)	late century		5%		23%		20%		9%		12%

Peaks for Annual Frequency Analysis
DSN1 7096 1H FLOW /HUMPTULIPS RIVER/BELOW HIGHWAY 101/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN2 3158 1H FLOW /NORTH FORK NEWAUKUM/NEAR FOREST/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN3 6101 1H FLOW /SKOOKUMCHUCK RIVER/NEAR BUCODA/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN4 1404 1H FLOW /SOUTH FORK CHEHALIS/NEAR WILDWOOD/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN5 6600 1H FLOW /SOUTH FORK NEWAUKUM/NEAR ONALASKA/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/

	Return Period	DSN1 7982 1H FLOW /HUMPTULIPS RIVER/BELOW HIGHWAY 101/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN2 7540 1H FLOW /NORTH FORK NEWAUKUM/NEAR FOREST/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN3 4446 1H FLOW /SKOOKUMCHUCK RIVER/NEAR BUCODA/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN4 8032 1H FLOW /SOUTH FORK CHEHALIS/NEAR WILDWOOD/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN5 996 1H FLOW /SOUTH FORK NEWAUKUM/NEAR ONALASKA/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change
1970-2015	2	15990		3422		9254		3904		7158	
	5	21153		5179		13411		5074		9947	
	10	24788		6580		16482		5802		12028	
	25	29637		8645		20730		6680		14939	
	50	33441		10416		24167	USGS Jan 09 10,500 cfs	7307		17320	
	100	37412	USGS Jan 09 41,200 cfs	12399	USGS Jan 09 5,700 cfs	27842	USGS Feb 96 11,300 cfs	7915	USGS Jan 09 6,870 cfs	19890	USGS Jan 09 8,800 cfs
	500	47455	USGS Nov 06 41,600 cfs	18001		37471		9283	USGS Dec 07 12,200 cfs	26739	
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2016 - 2060	2	17604	10%	4070	19%	10014	8%	4313	10%	7817	9%
	5	23271	10%	6006	16%	14622	9%	5745	13%	10761	8%
	10	27175	10%	7393	12%	18120	10%	6801	17%	12672	5%
	25	32291	9%	9257	7%	23073	11%	8263	24%	15044	1%
	50	36241	8%	10723	3%	27166	12%	9449	29%	16783	-3%
	100	40313	8%	12255	-1%	31618	14%	10720	35%	18501	-7%
	500	50405	6%	16114	-10%	43614	16%	14074	52%	22470	-16%
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2055 - 2099	2	18776	17%	3742	9%	9048	-2%	4425	13%	7564	6%
	5	23608	12%	5729	11%	13161	-2%	5779	14%	10693	7%
	10	26745	8%	7225	10%	16342	-1%	6645	15%	12912	7%
	25	30670	3%	9321	8%	20917	1%	7711	15%	15881	6%
	50	33579	0%	11031	6%	24755	2%	8490	16%	18212	5%
	100	36484	-2%	12872	4%	28981	4%	9257	17%	20645	4%
	500	43339	-9%	17729	-2%	40596	8%	11028	19%	26782	0%
Average (2-100)	mid century		9%		9%		11%		22%		2%
Average (2-100)	late century		6%		8%		0%		15%		6%

Peaks for Annual Frequency Analysis
DSN1 1388 1H FLOW /CHEHALIS RIVER/NEAR PORTER/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN2 4819 1H FLOW /CHEHALIS RIVER/NEAR SATSOP/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN3 6701 1H FLOW /SKOOKUMCHUCK RIVER/NEAR VAIL/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN4 337 1H FLOW /WYNOOCHEE RIVER/ABOVE BLACK CREEK/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN5 4170 1H FLOW /WYNOOCHEE RIVER/NEAR GRISDALE/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/

	Return Period	DSN1 1831 1H FLOW /CHEHALIS RIVER/NEAR PORTER/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN2 4256 1H FLOW /CHEHALIS RIVER/NEAR SATSOP/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN3 3686 1H FLOW /SKOOKUMCHUCK RIVER/NEAR VAIL/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN4 7029 1H FLOW /WYNOOCHEE RIVER/ABOVE BLACK CREEK/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change	DSN5 6526 1H FLOW /WYNOOCHEE RIVER/NEAR GRISDALE/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/ Peak	Change
1970-2015	2	72347		87009		8135		18189		11745	
	5	96650		120663		11118		24408		14448	
	10	111714		143677		13227		28743		16138	
	25	129739		173555		16045		34474		18190	
	50	142524		196382		18258		38933		19671	
	100	154825		219695		20569		43557		21120	
	500	182153		276527		26415		55122		24433	
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2016 - 2060	2	80940	12%	97326	12%	8905	9%	20716	14%	12795	9%
	5	112409	16%	135417	12%	12227	10%	26737	10%	16342	13%
	10	133464	19%	162119	13%	14379	9%	30810	7%	18723	16%
	25	160278	24%	197522	14%	17048	6%	36074	5%	21781	20%
	50	180401	27%	225102	15%	19001	4%	40089	3%	24100	23%
	100	200651	30%	253716	15%	20929	2%	44188	1%	26459	25%
	500	248865	37%	325243	18%	25379	-4%	54203	-2%	32186	32%
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2055 - 2099	2	71707	-1%	88365	2%	8515	5%	21144	16%	13513	15%
	5	103407	7%	124935	4%	12022	8%	26501	9%	16605	15%
	10	127246	14%	152601	6%	14452	9%	30045	5%	18578	15%
	25	160748	24%	191704	10%	17638	10%	34546	0%	21014	16%
	50	188254	32%	223994	14%	20093	10%	37928	-3%	22800	16%
	100	218022	41%	259117	18%	22616	10%	41341	-5%	24567	16%
	500	297581	63%	353812	28%	28827	9%	49534	-10%	28685	17%
Average (2-100)	mid century		21%		13%		7%		7%		18%
Average (2-100)	late century		19%		9%		9%		4%		15%

Summary by Quantile

Mid Century (2016-2060 vs 1970-2015)

	Return Period	Average	Minimum	Maximum
2016 - 2060	2	12%	8%	20%
	5	13%	8%	18%
	10	13%	5%	20%
	25	13%	1%	24%
	50	12%	-3%	29%
	100	12%	-7%	35%
	500	13%	-16%	52%

Late Century (2055-2099 vs 1970-2015)

	Return Period	Average	Minimum	Maximum
2055 - 2099	2	9%	-2%	21%
	5	9%	-2%	19%
	10	10%	-1%	22%
	25	11%	0%	26%
	50	12%	-3%	32%
	100	13%	-5%	41%
	500	16%	-10%	63%

Peaks for Annual Frequency Analysis
DSN1 1040 1H FLOW /CHEHALIS RIVER/AT MOUTH/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN2 6005 1H FLOW /CHEHALIS RIVER/NEAR DOTY/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN3 2427 1H FLOW /CHEHALIS RIVER/NEAR GRAND MOUND/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN4 3168 1H FLOW /NEWAUKUM RIVER/NEAR CHEHALIS/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN5 4608 1H FLOW /SATSOP RIVER/NEAR SATSOP/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/

Average (mid century 15 sites) =	12%
Minimum (mid century 15 sites) =	-4%
Maximum (mid century 15 sites) =	24%
Average (late century 15 sites) =	15%
Minimum (late century 15 sites) =	1%
Maximum (late century 15 sites) =	29%

	Return Period	DSN1 1040 1H FLOW /CHEHALIS RIVER/AT MOUTH/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN2 6005 1H FLOW /CHEHALIS RIVER/NEAR DOTY/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN3 2427 1H FLOW /CHEHALIS RIVER/NEAR GRAND MOUND/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN4 3168 1H FLOW /NEWAUKUM RIVER/NEAR CHEHALIS/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN5 4608 1H FLOW /SATSOP RIVER/NEAR SATSOP/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/	
1970-2015	Period	Peak		Peak		Peak		Peak		Peak	
	2	68419		6662		29231		4016		14530	
	5	91038		8349		38556		5732		19388	
	10	106033		9347		44281		6959		22759	
	25	125058		10503		51088		8610		27202	
	50	139311		11302		55891		9912		30648	
	100	153653		12055		60494		11276		34214	
	500	187853		13683		70664		14736		43102	
2016 - 2060	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	80281	17%	7618	14%	34845	19%	4640	16%	15953	10%
	5	104724	15%	9811	18%	46159	20%	6520	14%	20254	4%
	10	120333	13%	11261	20%	53467	21%	7847	13%	23068	1%
	25	139549	12%	13100	25%	62539	22%	9617	12%	26608	-2%
	50	153565	10%	14479	28%	69203	24%	11003	11%	29244	-5%
	100	167371	9%	15869	32%	75801	25%	12446	10%	31886	-7%
	500	199234	6%	19194	40%	91146	29%	16073	9%	38155	-11%
2055 - 2099	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	75727	11%	7329	10%	31693	8%	4124	3%	16311	12%
	5	100396	10%	9696	16%	43556	13%	6021	5%	20848	8%
	10	119250	12%	11467	23%	52700	19%	7492	8%	24087	6%
	25	146102	17%	13947	33%	65827	29%	9613	12%	28455	5%
	50	168430	21%	15979	41%	76824	37%	11395	15%	31915	4%
	100	192862	26%	18176	51%	88930	47%	13361	18%	35557	4%
	500	259428	38%	24048	76%	122224	73%	18779	27%	44888	4%
Average (2-100)	mid century		13%		23%		22%		13%		0%
Average (2-100)	late century		16%		29%		26%		10%		6%

Peaks for Annual Frequency Analysis
DSN1 7096 1H FLOW /HUMPTULIPS RIVER/BELOW HIGHWAY 101/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN2 3158 1H FLOW /NORTH FORK NEWAUKUM/NEAR FOREST/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN3 6101 1H FLOW /SKOOKUMCHUCK RIVER/NEAR BUCODA/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN4 1404 1H FLOW /SOUTH FORK CHEHALIS/NEAR WILDWOOD/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN5 6600 1H FLOW /SOUTH FORK NEWAUKUM/NEAR ONALASKA/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/

	Return Period	DSN1 7096 1H FLOW /HUMPTULIPS RIVER/BELOW HIGHWAY 101/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN2 3158 1H FLOW /NORTH FORK NEWAUKUM/NEAR FOREST/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN3 6101 1H FLOW /SKOOKUMCHUCK RIVER/NEAR BUCODA/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN4 1404 1H FLOW /SOUTH FORK CHEHALIS/NEAR WILDWOOD/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN5 6600 1H FLOW /SOUTH FORK NEWAUKUM/NEAR ONALASKA/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/	
1970-2015	Period	Peak		Peak		Peak		Peak		Peak	
	2	6462		1136		3576		1067		1780	
	5	8626		1617		5048		1346		2511	
	10	10257		1952		6045		1525		3029	
	25	12553		2395		7325		1744		3721	
	50	14444		2737		8294	USGS Jan 09 10,500 cfs	1905		4264	
	100	16497	USGS Jan 09 41,200 cfs	3089	USGS Jan 09 5,700 cfs	9273	USGS Feb 96 11,300 cfs	2064	USGS Jan 09 6,870 cfs	4831	USGS Jan 09 8,800 cfs
	500	22023	USGS Nov 06 41,600 cfs	3961		11625		2431	USGS Dec 07 12,200 cfs	6258	
2016 - 2060	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	7218	12%	1298	14%	4225	18%	1247	17%	1976	11%
	5	9021	5%	1831	13%	5878	16%	1622	20%	2795	11%
	10	10162	-1%	2199	13%	6985	16%	1866	22%	3376	11%
	25	11559	-8%	2682	12%	8397	15%	2172	25%	4154	12%
	50	12576	-13%	3053	12%	9458	14%	2399	26%	4764	12%
	100	13576	-18%	3435	11%	10526	14%	2625	27%	5402	12%
	500	15882	-28%	4374	10%	13070	12%	3158	30%	7010	12%
2055 - 2099	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	7250	12%	1156	2%	3693	3%	1213	14%	1762	-1%
	5	9146	6%	1694	5%	5418	7%	1606	19%	2588	3%
	10	10485	2%	2103	8%	6733	11%	1890	24%	3232	7%
	25	12277	-2%	2684	12%	8599	17%	2274	30%	4162	12%
	50	13686	-5%	3165	16%	10146	22%	2580	35%	4947	16%
	100	15160	-8%	3689	19%	11831	28%	2904	41%	5815	20%
	500	18901	-14%	5103	29%	16386	41%	3739	54%	8216	31%
Average (2-100)	mid century		-4%		12%		15%		23%		12%
Average (2-100)	late century		1%		10%		15%		27%		10%

Peaks for Annual Frequency Analysis
DSN1 1388 1H FLOW /CHEHALIS RIVER/NEAR PORTER/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN2 4819 1H FLOW /CHEHALIS RIVER/NEAR SATSOP/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN3 6701 1H FLOW /SKOOKUMCHUCK RIVER/NEAR VAIL/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN4 337 1H FLOW /WYNOOCHEE RIVER/ABOVE BLACK CREEK/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/
DSN5 4170 1H FLOW /WYNOOCHEE RIVER/NEAR GRISDALE/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/

	Return Period	DSN1 1388 1H FLOW /CHEHALIS RIVER/NEAR PORTER/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN2 4819 1H FLOW /CHEHALIS RIVER/NEAR SATSOP/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN3 6701 1H FLOW /SKOOKUMCHUCK RIVER/NEAR VAIL/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN4 337 1H FLOW /WYNOOCHEE RIVER/ABOVE BLACK CREEK/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/		DSN5 4170 1H FLOW /WYNOOCHEE RIVER/NEAR GRISDALE/FLOW//1HOUR/ACCESS 1.0 RCP 4.5/	
1970-2015	Period	Peak		Peak		Peak		Peak		Peak	
	2	36268		52412		2096		8593		3597	
	5	47859		69259		2939		11379		4679	
	10	54978		80121		3521		13383		5432	
	25	63444		93588		4280		16102		6426	
	50	69418		103468		4864		18268		7198	
	100	75144		113244		5462		20559		7999	
	500	87799		135950		6929		26466		10004	
2016 - 2060	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	43887	21%	61784	18%	2338	12%	9537	11%	4113	14%
	5	58249	22%	81308	17%	3307	13%	11897	5%	5101	9%
	10	67539	23%	94145	18%	3980	13%	13387	0%	5709	5%
	25	79084	25%	110332	18%	4863	14%	15211	-6%	6437	0%
	50	87572	26%	122396	18%	5544	14%	16537	-9%	6956	-3%
	100	95982	28%	134487	19%	6245	14%	17840	-13%	7458	-7%
	500	115558	32%	163150	20%	7971	15%	20842	-21%	8589	-14%
2055 - 2099	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	40031	10%	58562	12%	2064	-2%	9669	13%	4187	16%
	5	54777	14%	78503	13%	3045	4%	12187	7%	5288	13%
	10	65878	20%	93576	17%	3812	8%	13965	4%	6020	11%
	25	81514	28%	114866	23%	4925	15%	16342	1%	6955	8%
	50	94389	36%	132443	28%	5865	21%	18210	0%	7659	6%
	100	108366	44%	151566	34%	6907	26%	20163	-2%	8373	5%
	500	145955	66%	203186	49%	9798	41%	25119	-5%	10094	1%
Average (2-100)	mid century		24%		18%		13%		-2%		3%
Average (2-100)	late century		26%		21%		12%		4%		10%

Summary by Quantile

Mid Century (2016-2060 vs 1970-2015)

	Return Period	Average	Minimum	Maximum
2016 - 2060	2	15%	10%	21%
	5	13%	4%	22%
	10	13%	-1%	23%
	25	12%	-8%	25%
	50	11%	-13%	28%
	100	10%	-18%	32%
	500	9%	-28%	40%

Late Century (2055-2099 vs 1970-2015)

	Return Period	Average	Minimum	Maximum
2055 - 2099	2	8%	-2%	16%
	5	10%	3%	19%
	10	12%	2%	24%
	25	16%	-2%	33%
	50	20%	-5%	41%
	100	24%	-8%	51%
	500	34%	-14%	76%

Peaks for Annual Frequency Analysis
DSN1 3229 1H FLOW /CHEHALIS RIVER/AT MOUTH/FLOW//1HOUR/GFDL RCP 8.5/
DSN2 1309 1H FLOW /CHEHALIS RIVER/NEAR DOTY/FLOW//1HOUR/GFDL RCP 8.5/
DSN3 6237 1H FLOW /CHEHALIS RIVER/NEAR GRAND MOUND/FLOW//1HOUR/GFDL RCP 8.5/
DSN4 6167 1H FLOW /NEWAUKUM RIVER/NEAR CHEHALIS/FLOW//1HOUR/GFDL RCP 8.5/
DSN5 920 1H FLOW /SATSOP RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/

Average (mid century 15 sites) =	11%
Minimum (mid century 15 sites) =	-1%
Maximum (mid century 15 sites) =	31%
Average (late century 15 sites) =	26%
Minimum (late century 15 sites) =	14%
Maximum (late century 15 sites) =	47%

	Return Period	DSN1 3229 1H FLOW /CHEHALIS RIVER/AT MOUTH/FLOW//1HOUR/GFDL RCP 8.5/		DSN2 1309 1H FLOW /CHEHALIS RIVER/NEAR DOTY/FLOW//1HOUR/GFDL RCP 8.5/		DSN3 6237 1H FLOW /CHEHALIS RIVER/NEAR GRAND MOUND/FLOW//1HOUR/GFDL RCP 8.5/		DSN4 6167 1H FLOW /NEWAUKUM RIVER/NEAR CHEHALIS/FLOW//1HOUR/GFDL RCP 8.5/		DSN5 920 1H FLOW /SATSOP RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/	
		Peak		Peak		Peak		Peak		Peak	
1970-2015	2	85550		17937		51138		9772		31895	
	5	107220		22838		67735		13774		39870	
	10	120954		26397		79431		16418		44804	
	25	137807		31257		95044		19742		50739	
	50	150081		35150		107298		22204		54984	
	100	162168		39284		120100		24653		59106	
	500	190088		50021		152502		30377		68419	
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2016 - 2060	2	92662	8%	19949	11%	57446	12%	11253	15%	35503	11%
	5	116493	9%	24830	9%	78503	16%	15880	15%	43978	10%
	10	131298	9%	27417	4%	90427	14%	18790	14%	48827	9%
	25	149164	8%	30142	-4%	103517	9%	22289	13%	54295	7%
	50	161979	8%	31862	-9%	112043	4%	24773	12%	57980	5%
	100	174443	8%	33368	-15%	119678	0%	27158	10%	61391	4%
	500	202686	7%	36269	-27%	134792	-12%	32428	7%	68546	0%
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2055 - 2099	2	101988	19%	20724	16%	63438	24%	13361	37%	38165	20%
	5	132759	24%	27463	20%	86189	27%	18136	32%	50524	27%
	10	149105	23%	31409	19%	99753	26%	21277	30%	57756	29%
	25	166195	21%	35904	15%	115386	21%	25228	28%	65990	30%
	50	176853	18%	38948	11%	126071	17%	28162	27%	71562	30%
	100	186079	15%	41767	6%	136034	13%	31092	26%	76722	30%
	500	203444	7%	47667	-5%	157078	3%	37989	25%	87519	28%
Average (2-100)	mid century		8%		-1%		9%		13%		8%
Average (2-100)	late century		20%		14%		22%		30%		28%

Peaks for Annual Frequency Analysis
DSN1 7982 1H FLOW /HUMPTULIPS RIVER/BELOW HIGHWAY 101/FLOW//1HOUR/GFDL RCP 8.5/
DSN2 7540 1H FLOW /NORTH FORK NEWAUKUM/NEAR FOREST/FLOW//1HOUR/GFDL RCP 8.5/
DSN3 4446 1H FLOW /SKOOKUMCHUCK RIVER/NEAR BUCODA/FLOW//1HOUR/GFDL RCP 8.5/
DSN4 8032 1H FLOW /SOUTH FORK CHEHALIS/NEAR WILDWOOD/FLOW//1HOUR/GFDL RCP 8.5/
DSN5 996 1H FLOW /SOUTH FORK NEWAUKUM/NEAR ONALASKA/FLOW//1HOUR/GFDL RCP 8.5/

	Return Period	DSN1 7982 1H FLOW /HUMPTULIPS RIVER/BELOW HIGHWAY 101/FLOW//1HOUR/GFDL RCP 8.5/		DSN2 7540 1H FLOW /NORTH FORK NEWAUKUM/NEAR FOREST/FLOW//1HOUR/GFDL RCP 8.5/		DSN3 4446 1H FLOW /SKOOKUMCHUCK RIVER/NEAR BUCODA/FLOW//1HOUR/GFDL RCP 8.5/		DSN4 8032 1H FLOW /SOUTH FORK CHEHALIS/NEAR WILDWOOD/FLOW//1HOUR/GFDL RCP 8.5/		DSN5 996 1H FLOW /SOUTH FORK NEWAUKUM/NEAR ONALASKA/FLOW//1HOUR/GFDL RCP 8.5/	
		Peak		Peak		Peak		Peak		Peak	
1970-2015	2	14906		2853		7246		3396		5954	
	5	18443		4095		9677		4384		8079	
	10	20415		4885		11146		4981		9444	
	25	22588		5843		12866		5683		11126	
	50	24022		6528		14060	USGS Jan 09 10,500 cfs	6173		12351	
	100	25326	USGS Jan 09 41,200 cfs	7189	USGS Jan 09 5,700 cfs	15189	USGS Feb 96 11,300 cfs	6640	USGS Jan 09 6,870 cfs	13556	USGS Jan 09 8,800 cfs
	500	27987	USGS Nov 06 41,600 cfs	8659		17629		7663	USGS Dec 07 12,200 cfs	16321	
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2016 - 2060	2	16451	10%	3277	15%	8436	16%	3758	11%	6989	17%
	5	20181	9%	4745	16%	12081	25%	4948	13%	9348	16%
	10	22300	9%	5685	16%	14457	30%	5566	12%	10775	14%
	25	24677	9%	6830	17%	17403	35%	6196	9%	12446	12%
	50	26274	9%	7651	17%	19555	39%	6579	7%	13608	10%
	100	27747	10%	8445	17%	21668	43%	6903	4%	14707	8%
	500	30826	10%	10217	18%	26507	50%	7492	-2%	17083	5%
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2055 - 2099	2	17850	20%	3930	38%	9929	37%	3876	14%	8167	37%
	5	22420	22%	5448	33%	13559	40%	5380	23%	10710	33%
	10	25061	23%	6486	33%	16012	44%	6290	26%	12265	30%
	25	28060	24%	7833	34%	19170	49%	7351	29%	14107	27%
	50	30092	25%	8863	36%	21566	53%	8081	31%	15405	25%
	100	31980	26%	9914	38%	23998	58%	8767	32%	16646	23%
	500	35964	28%	12475	44%	29880	69%	10225	33%	19381	19%
Average (2-100)	mid century		10%		16%		31%		9%		13%
Average (2-100)	late century		23%		35%		47%		26%		29%

Peaks for Annual Frequency Analysis
DSN1 1831 1H FLOW /CHEHALIS RIVER/NEAR PORTER/FLOW//1HOUR/GFDL RCP 8.5/
DSN2 4256 1H FLOW /CHEHALIS RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/
DSN3 3686 1H FLOW /SKOOKUMCHUCK RIVER/NEAR VAIL/FLOW//1HOUR/GFDL RCP 8.5/
DSN4 7029 1H FLOW /WYNOOCHEE RIVER/ABOVE BLACK CREEK/FLOW//1HOUR/GFDL RCP 8.5/
DSN5 6526 1H FLOW /WYNOOCHEE RIVER/NEAR GRISDALE/FLOW//1HOUR/GFDL RCP 8.5/

	Return Period	DSN1 1831 1H FLOW /CHEHALIS RIVER/NEAR PORTER/FLOW//1HOUR/GFDL RCP 8.5/		DSN2 4256 1H FLOW /CHEHALIS RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/		DSN3 3686 1H FLOW /SKOOKUMCHUCK RIVER/NEAR VAIL/FLOW//1HOUR/GFDL RCP 8.5/		DSN4 7029 1H FLOW /WYNOOCHEE RIVER/ABOVE BLACK CREEK/FLOW//1HOUR/GFDL RCP 8.5/		DSN5 6526 1H FLOW /WYNOOCHEE RIVER/NEAR GRISDALE/FLOW//1HOUR/GFDL RCP 8.5/	
		Peak		Peak		Peak		Peak		Peak	
1970-2015	2	54330		69408		6650		16859		11079	
	5	71167		88386		9038		20932		13172	
	10	82688		100829		10573		23147		14276	
	25	97705		116510		12466		25537		15443	
	50	109245		128205		13846		27081		16186	
	100	121099		139938		15203		28460		16842	
	500	150316		167831		18321		31199		18126	
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2016 - 2060	2	60853	12%	75886	9%	7787	17%	18193	8%	11716	6%
	5	82744	16%	98039	11%	10544	17%	22917	9%	13668	4%
	10	95453	15%	111761	11%	12185	15%	25653	11%	14763	3%
	25	109745	12%	128240	10%	14072	13%	28764	13%	15986	4%
	50	119282	9%	139991	9%	15360	11%	30875	14%	16806	4%
	100	128000	6%	151358	8%	16561	9%	32838	15%	17563	4%
	500	145837	-3%	176871	5%	19093	4%	36983	19%	19150	6%
	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
2055 - 2099	2	67552	24%	83448	20%	9038	36%	20179	20%	12704	15%
	5	90490	27%	110859	25%	11930	32%	25864	24%	15441	17%
	10	103666	25%	125630	25%	13706	30%	29198	26%	17137	20%
	25	118381	21%	141207	21%	15819	27%	33021	29%	19182	24%
	50	128149	17%	150985	18%	17310	25%	35633	32%	20650	28%
	100	137044	13%	159486	14%	18740	23%	38074	34%	22080	31%
	500	155153	3%	175574	5%	21899	20%	43265	39%	25329	40%
Average (2-100)	mid century		12%		10%		14%		12%		4%
Average (2-100)	late century		21%		21%		29%		27%		22%

Summary by Quantile

Mid Century (2016-2060 vs 1970-2015)

	Return Period	Average	Minimum	Maximum
2016 - 2060	2	12%	6%	17%
	5	13%	4%	25%
	10	12%	3%	30%
	25	11%	-4%	35%
	50	10%	-9%	39%
	100	9%	-15%	43%
	500	6%	-27%	50%

Late Century (2055-2099 vs 1970-2015)

	Return Period	Average	Minimum	Maximum
2055 - 2099	2	25%	14%	38%
	5	27%	17%	40%
	10	27%	19%	44%
	25	27%	15%	49%
	50	26%	11%	53%
	100	26%	6%	58%
	500	24%	-5%	69%

Peaks for Annual Frequency Analysis
DSN1 3229 1H FLOW /CHEHALIS RIVER/AT MOUTH/FLOW//1HOUR/GFDL RCP 8.5/
DSN2 1309 1H FLOW /CHEHALIS RIVER/NEAR DOTY/FLOW//1HOUR/GFDL RCP 8.5/
DSN3 6237 1H FLOW /CHEHALIS RIVER/NEAR GRAND MOUND/FLOW//1HOUR/GFDL RCP 8.5/
DSN4 6167 1H FLOW /NEWAUKUM RIVER/NEAR CHEHALIS/FLOW//1HOUR/GFDL RCP 8.5/
DSN5 920 1H FLOW /SATSOP RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/

Average (mid century 15 sites) =	17%	Average (late century 15 sites) =	28%
Minimum (mid century 15 sites) =	7%	Minimum (late century 15 sites) =	16%
Maximum (mid century 15 sites) =	32%	Maximum (late century 15 sites) =	44%

	Return Period	DSN1 3229 1H FLOW /CHEHALIS RIVER/AT MOUTH/FLOW//1HOUR/GFDL RCP 8.5/		DSN2 1309 1H FLOW /CHEHALIS RIVER/NEAR DOTY/FLOW//1HOUR/GFDL RCP 8.5/		DSN3 6237 1H FLOW /CHEHALIS RIVER/NEAR GRAND MOUND/FLOW//1HOUR/GFDL RCP 8.5/		DSN4 6167 1H FLOW /NEWAUKUM RIVER/NEAR CHEHALIS/FLOW//1HOUR/GFDL RCP 8.5/		DSN5 920 1H FLOW /SATSOP RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/	
1970-2015	Period	Peak		Peak		Peak		Peak		Peak	
	2	70459		7871		31848		4550		55246	
	5	87428		10002		40875		6085		68980	
	10	98567		11487		46955		7129		77851	
	25	112633		13452		54786		8483		88905	
	50	123146		14982		60742		9517		97070	
	100	133715		16571		66810		10574		105200	
	500	158930		20557		81583		13157		124314	
2016 - 2060	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	79405	13%	8899	13%	37752	19%	5498	21%	63150	14%
	5	101204	16%	11363	14%	48630	19%	7566	24%	80228	16%
	10	113287	15%	12730	11%	55195	18%	8875	24%	90181	16%
	25	126478	12%	14224	6%	62906	15%	10466	23%	101544	14%
	50	135078	10%	15199	1%	68293	12%	11608	22%	109280	13%
	100	142813	7%	16076	-3%	73419	10%	12717	20%	116491	11%
	500	158304	0%	17834	-13%	84630	4%	15213	16%	131771	6%
2055 - 2099	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	82872	18%	9272	18%	39425	24%	5858	29%	65572	19%
	5	105112	20%	12457	25%	52606	29%	8039	32%	84714	23%
	10	119021	21%	14585	27%	60968	30%	9518	34%	96849	24%
	25	135885	21%	17299	29%	71182	30%	11428	35%	111712	26%
	50	148030	20%	19341	29%	78568	29%	12879	35%	122505	26%
	100	159879	20%	21403	29%	85788	28%	14356	36%	133101	27%
	500	186846	18%	26347	28%	102238	25%	17936	36%	157439	27%
Average (2-100)	mid century		12%		7%		15%		23%		14%
Average (2-100)	late century		20%		26%		28%		33%		24%

Peaks for Annual Frequency Analysis
DSN1 7982 1H FLOW /HUMPTULIPS RIVER/BELOW HIGHWAY 101/FLOW//1HOUR/GFDL RCP 8.5/
DSN2 7540 1H FLOW /NORTH FORK NEWAUKUM/NEAR FOREST/FLOW//1HOUR/GFDL RCP 8.5/
DSN3 4446 1H FLOW /SKOOKUMCHUCK RIVER/NEAR BUCODA/FLOW//1HOUR/GFDL RCP 8.5/
DSN4 8032 1H FLOW /SOUTH FORK CHEHALIS/NEAR WILDWOOD/FLOW//1HOUR/GFDL RCP 8.5/
DSN5 996 1H FLOW /SOUTH FORK NEWAUKUM/NEAR ONALASKA/FLOW//1HOUR/GFDL RCP 8.5/

	Return Period	DSN1 7982 1H FLOW /HUMPTULIPS RIVER/BELOW HIGHWAY 101/FLOW//1HOUR/GFDL RCP 8.5/		DSN2 7540 1H FLOW /NORTH FORK NEWAUKUM/NEAR FOREST/FLOW//1HOUR/GFDL RCP 8.5/		DSN3 4446 1H FLOW /SKOOKUMCHUCK RIVER/NEAR BUCODA/FLOW//1HOUR/GFDL RCP 8.5/		DSN4 8032 1H FLOW /SOUTH FORK CHEHALIS/NEAR WILDWOOD/FLOW//1HOUR/GFDL RCP 8.5/		DSN5 996 1H FLOW /SOUTH FORK NEWAUKUM/NEAR ONALASKA/FLOW//1HOUR/GFDL RCP 8.5/	
1970-2015	Period	Peak		Peak		Peak		Peak		Peak	
	2	8925		1298		4164		1332		2142	
	5	10993		1747		5465		1703		2862	
	10	12200		2053		6300		1957		3351	
	25	13587		2453		7331		2289		3984	
	50	14537		2759		8085	USGS Jan 09 10,500 cfs	2545		4468	
	100	15429	USGS Jan 09 41,200 cfs	3072	USGS Jan 09 5,700 cfs	8830	USGS Feb 96 11,300 cfs	2808	USGS Jan 09 6,870 cfs	4962	USGS Jan 09 8,800 cfs
	500	17343	USGS Nov 06 41,600 cfs	3842		10553		3460	USGS Dec 07 12,200 cfs	6169	
2016 - 2060	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	9011	1%	1590	23%	5025	21%	1535	15%	2513	17%
	5	11435	4%	2208	26%	7004	28%	1970	16%	3465	21%
	10	13088	7%	2602	27%	8299	32%	2200	12%	4156	24%
	25	15238	12%	3082	26%	9919	35%	2438	6%	5102	28%
	50	16888	16%	3429	24%	11112	37%	2586	2%	5860	31%
	100	18581	20%	3766	23%	12295	39%	2713	-3%	6665	34%
	500	22750	31%	4529	18%	15045	43%	2953	-15%	8756	42%
2055 - 2099	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	10004	12%	1695	31%	5330	28%	1518	14%	2776	30%
	5	12486	14%	2354	35%	7477	37%	2100	23%	3810	33%
	10	14020	15%	2806	37%	8958	42%	2515	28%	4528	35%
	25	15863	17%	3393	38%	10893	49%	3073	34%	5473	37%
	50	17181	18%	3842	39%	12380	53%	3515	38%	6204	39%
	100	18460	20%	4301	40%	13904	57%	3978	42%	6959	40%
	500	21347	23%	5421	41%	17643	67%	5158	49%	8831	43%
Average (2-100)	mid century		10%		25%		32%		8%		26%
Average (2-100)	late century		16%		37%		44%		30%		36%

Peaks for Annual Frequency Analysis
DSN1 1831 1H FLOW /CHEHALIS RIVER/NEAR PORTER/FLOW//1HOUR/GFDL RCP 8.5/
DSN2 4256 1H FLOW /CHEHALIS RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/
DSN3 3686 1H FLOW /SKOOKUMCHUCK RIVER/NEAR VAIL/FLOW//1HOUR/GFDL RCP 8.5/
DSN4 7029 1H FLOW /WYNOOCHEE RIVER/ABOVE BLACK CREEK/FLOW//1HOUR/GFDL RCP 8.5/
DSN5 6526 1H FLOW /WYNOOCHEE RIVER/NEAR GRISDALE/FLOW//1HOUR/GFDL RCP 8.5/

	Return Period	DSN1 1831 1H FLOW /CHEHALIS RIVER/NEAR PORTER/FLOW//1HOUR/GFDL RCP 8.5/		DSN2 4256 1H FLOW /CHEHALIS RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/		DSN3 3686 1H FLOW /SKOOKUMCHUCK RIVER/NEAR VAIL/FLOW//1HOUR/GFDL RCP 8.5/		DSN4 7029 1H FLOW /WYNOOCHEE RIVER/ABOVE BLACK CREEK/FLOW//1HOUR/GFDL RCP 8.5/		DSN5 6526 1H FLOW /WYNOOCHEE RIVER/NEAR GRISDALE/FLOW//1HOUR/GFDL RCP 8.5/	
1970-2015	Period	Peak		Peak		Peak		Peak		Peak	
	2	38695		55246		2527		11330		5161	
	5	49168		68980		3368		13648		6049	
	10	56170		77851		3925		15011		6560	
	25	65135		88905		4634		16588		7144	
	50	71918		97070		5165		17679		7543	
	100	78801		105200		5700		18711		7917	
	500	95460		124314		6976		20954		8719	
2016 - 2060	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	45111	17%	63150	14%	2973	18%	11614	3%	5255	2%
	5	57621	17%	80228	16%	4121	22%	14440	6%	6372	5%
	10	64940	16%	90181	16%	4942	26%	16337	9%	7093	8%
	25	73320	13%	101544	14%	6047	31%	18774	13%	7991	12%
	50	79037	10%	109280	13%	6922	34%	20624	17%	8654	15%
	100	84373	7%	116491	11%	7841	38%	22506	20%	9315	18%
	500	95707	0%	131771	6%	10184	46%	27082	29%	10870	25%
2055 - 2099	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	46613	20%	65572	19%	3269	29%	12622	11%	5533	7%
	5	61883	26%	84714	23%	4541	35%	15743	15%	6949	15%
	10	71763	28%	96849	24%	5413	38%	17714	18%	7907	21%
	25	84042	29%	111712	26%	6545	41%	20125	21%	9146	28%
	50	93071	29%	122505	26%	7411	43%	21878	24%	10091	34%
	100	102017	29%	133101	27%	8296	46%	23600	26%	11057	40%
	500	122847	29%	157439	27%	10456	50%	27569	32%	13419	54%
Average (2-100)	mid century		13%		14%		28%		11%		10%
Average (2-100)	late century		27%		24%		39%		19%		24%

Summary by Quantile

Mid Century (2016-2060 vs 1970-2015)

	Return Period	Average	Minimum	Maximum
2016 - 2060	2	14%	1%	23%
	5	17%	4%	28%
	10	17%	7%	32%
	25	17%	6%	35%
	50	17%	1%	37%
	100	17%	-3%	39%
	500	16%	-15%	46%

Late Century (2055-2099 vs 1970-2015)

	Return Period	Average	Minimum	Maximum
2055 - 2099	2	21%	7%	31%
	5	26%	14%	37%
	10	28%	15%	42%
	25	31%	17%	49%
	50	32%	18%	53%
	100	34%	20%	57%
	500	37%	18%	67%

Peaks for Annual Frequency Analysis	Average (mid century 15 sites) =	13%	Average (late century 15 sites) =	17%
DSN1 3229 1H FLOW /CHEHALIS RIVER/AT MOUTH/FLOW//1HOUR/GFDL RCP 8.5/	Minimum (mid century 15 sites) =	7%	Minimum (late century 15 sites) =	10%
DSN2 1309 1H FLOW /CHEHALIS RIVER/NEAR DOTY/FLOW//1HOUR/GFDL RCP 8.5/	Maximum (mid century 15 sites) =	25%	Maximum (late century 15 sites) =	23%
DSN3 6237 1H FLOW /CHEHALIS RIVER/NEAR GRAND MOUND/FLOW//1HOUR/GFDL RCP 8.5/				
DSN4 6167 1H FLOW /NEWAUKUM RIVER/NEAR CHEHALIS/FLOW//1HOUR/GFDL RCP 8.5/				
DSN5 920 1H FLOW /SATSOP RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/				

	Return Period	DSN1 3229 1H FLOW /CHEHALIS RIVER/AT MOUTH/FLOW//1HOUR/GFDL RCP 8.5/		DSN2 1309 1H FLOW /CHEHALIS RIVER/NEAR DOTY/FLOW//1HOUR/GFDL RCP 8.5/		DSN3 6237 1H FLOW /CHEHALIS RIVER/NEAR GRAND MOUND/FLOW//1HOUR/GFDL RCP 8.5/		DSN4 6167 1H FLOW /NEWAUKUM RIVER/NEAR CHEHALIS/FLOW//1HOUR/GFDL RCP 8.5/		DSN5 920 1H FLOW /SATSOP RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/	
1970-2015		Peak		Peak		Peak		Peak		Peak	
	2	57024		5257		22919		3092		12885	
	5	70505		6486		28448		4048		15664	
	10	79147		7289		32079		4772		17348	
	25	89857		8299		36665		5795		19343	
	50	97728		9053		40093		6638		20752	
	100	105538		9808		43540		7556		22107	
	500	123796		11604		51765		10032		25128	
2016 - 2060	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	63237	11%	5941	13%	26708	17%	3792	23%	13993	9%
	5	79372	13%	7391	14%	33441	18%	5042	25%	17025	9%
	10	88457	12%	8115	11%	37024	15%	5852	23%	18862	9%
	25	98540	10%	8837	6%	40809	11%	6859	18%	21041	9%
	50	105228	8%	9268	2%	43202	8%	7600	14%	22580	9%
	100	111334	5%	9629	-2%	45302	4%	8334	10%	24061	9%
	500	123864	0%	10275	-11%	49351	-5%	10046	0%	27362	9%
2055 - 2099	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	65156	14%	6072	16%	26583	16%	3840	24%	14319	11%
	5	81109	15%	7823	21%	33959	19%	4984	23%	17565	12%
	10	91169	15%	8905	22%	38702	21%	5696	19%	19544	13%
	25	103466	15%	10203	23%	44585	22%	6552	13%	21902	13%
	50	112394	15%	11127	23%	48908	22%	7163	8%	23574	14%
	100	121164	15%	12021	23%	53194	22%	7756	3%	25187	14%
	500	141349	14%	14023	21%	63197	22%	9089	-9%	28797	15%
Average (2-100)	mid century		10%		8%		12%		19%		9%
Average (2-100)	late century		15%		21%		20%		15%		13%

Peaks for Annual Frequency Analysis
DSN1 7982 1H FLOW /HUMPTULIPS RIVER/BELOW HIGHWAY 101/FLOW//1HOUR/GFDL RCP 8.5/
DSN2 7540 1H FLOW /NORTH FORK NEWAUKUM/NEAR FOREST/FLOW//1HOUR/GFDL RCP 8.5/
DSN3 4446 1H FLOW /SKOOKUMCHUCK RIVER/NEAR BUCODA/FLOW//1HOUR/GFDL RCP 8.5/
DSN4 8032 1H FLOW /SOUTH FORK CHEHALIS/NEAR WILDWOOD/FLOW//1HOUR/GFDL RCP 8.5/
DSN5 996 1H FLOW /SOUTH FORK NEWAUKUM/NEAR ONALASKA/FLOW//1HOUR/GFDL RCP 8.5/

	Return Period	DSN1 7982 1H FLOW /HUMPTULIPS RIVER/BELOW HIGHWAY 101/FLOW//1HOUR/GFDL RCP 8.5/		DSN2 7540 1H FLOW /NORTH FORK NEWAUKUM/NEAR FOREST/FLOW//1HOUR/GFDL RCP 8.5/		DSN3 4446 1H FLOW /SKOOKUMCHUCK RIVER/NEAR BUCODA/FLOW//1HOUR/GFDL RCP 8.5/		DSN4 8032 1H FLOW /SOUTH FORK CHEHALIS/NEAR WILDWOOD/FLOW//1HOUR/GFDL RCP 8.5/		DSN5 996 1H FLOW /SOUTH FORK NEWAUKUM/NEAR ONALASKA/FLOW//1HOUR/GFDL RCP 8.5/	
1970-2015		Peak		Peak		Peak		Peak		Peak	
	2	5908		874		2829		887		1393	
	5	7161		1146		3658		1095		1820	
	10	7937		1353		4266		1231		2144	
	25	8870		1644		5106		1403		2600	
	50	9539		1884		5784	USGS Jan 09 10,500 cfs	1530		2976	
	100	10191	USGS Jan 09 41,200 cfs	2146	USGS Jan 09 5,700 cfs	6510	USGS Feb 96 11,300 cfs	1659	USGS Jan 09 6,870 cfs	3384	USGS Jan 09 8,800 cfs
	500	11668	USGS Nov 06 41,600 cfs	2854		8417		1964	USGS Dec 07 12,200 cfs	4485	
2016 - 2060	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	6407	8%	1076	23%	3440	22%	998	13%	1650	18%
	5	7821	9%	1446	26%	4647	27%	1262	15%	2238	23%
	10	8621	9%	1693	25%	5438	27%	1399	14%	2625	22%
	25	9517	7%	2007	22%	6431	26%	1541	10%	3112	20%
	50	10118	6%	2244	19%	7166	24%	1628	6%	3473	17%
	100	10671	5%	2483	16%	7900	21%	1703	3%	3833	13%
	500	11825	1%	3057	7%	9622	14%	1844	-6%	4682	4%
2055 - 2099	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	6575	11%	1086	24%	3422	21%	1004	13%	1706	23%
	5	7910	10%	1426	24%	4533	24%	1319	21%	2232	23%
	10	8731	10%	1644	22%	5267	23%	1522	24%	2577	20%
	25	9716	10%	1913	16%	6196	21%	1773	26%	3010	16%
	50	10420	9%	2110	12%	6891	19%	1957	28%	3332	12%
	100	11102	9%	2305	7%	7588	17%	2139	29%	3654	8%
	500	12645	8%	2755	-3%	9248	10%	2559	30%	4414	-2%
Average (2-100)	mid century		7%		22%		25%		10%		19%
Average (2-100)	late century		10%		18%		21%		23%		17%

Peaks for Annual Frequency Analysis
DSN1 1831 1H FLOW /CHEHALIS RIVER/NEAR PORTER/FLOW//1HOUR/GFDL RCP 8.5/
DSN2 4256 1H FLOW /CHEHALIS RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/
DSN3 3686 1H FLOW /SKOOKUMCHUCK RIVER/NEAR VAIL/FLOW//1HOUR/GFDL RCP 8.5/
DSN4 7029 1H FLOW /WYNOOCHEE RIVER/ABOVE BLACK CREEK/FLOW//1HOUR/GFDL RCP 8.5/
DSN5 6526 1H FLOW /WYNOOCHEE RIVER/NEAR GRISDALE/FLOW//1HOUR/GFDL RCP 8.5/

	Return Period	DSN1 1831 1H FLOW /CHEHALIS RIVER/NEAR PORTER/FLOW//1HOUR/GFDL RCP 8.5/		DSN2 4256 1H FLOW /CHEHALIS RIVER/NEAR SATSOP/FLOW//1HOUR/GFDL RCP 8.5/		DSN3 3686 1H FLOW /SKOOKUMCHUCK RIVER/NEAR VAIL/FLOW//1HOUR/GFDL RCP 8.5/		DSN4 7029 1H FLOW /WYNOOCHEE RIVER/ABOVE BLACK CREEK/FLOW//1HOUR/GFDL RCP 8.5/		DSN5 6526 1H FLOW /WYNOOCHEE RIVER/NEAR GRISDALE/FLOW//1HOUR/GFDL RCP 8.5/	
1970-2015		Peak		Peak		Peak		Peak		Peak	
	2	28888		43068		1635		7658		3328	
	5	35857		53328		2129		9216		3879	
	10	40433		60052		2495		10173		4180	
	25	46212		68533		3001		11322		4510	
	50	50533		74865		3413		12143		4727	
	100	54877		81225		3854		12939		4924	
	500	65242		96380		5021		14740		5329	
2016 - 2060	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	32811	14%	48391	12%	1949	19%	8292	8%	3542	6%
	5	41328	15%	60447	13%	2649	24%	10073	9%	4228	9%
	10	46009	14%	67034	12%	3089	24%	11079	9%	4628	11%
	25	51091	11%	74159	8%	3620	21%	12201	8%	5089	13%
	50	54391	8%	78770	5%	4000	17%	12952	7%	5407	14%
	100	57349	5%	82897	2%	4367	13%	13643	5%	5706	16%
	500	63252	-3%	91108	-5%	5189	3%	15082	2%	6355	19%
2055 - 2099	Return Period	Peak	Change	Peak	Change	Peak	Change	Peak	Change	Peak	Change
	2	33242	15%	49494	15%	1992	22%	8594	12%	3719	12%
	5	42422	18%	62196	17%	2636	24%	10341	12%	4471	15%
	10	48320	20%	70263	17%	3052	22%	11392	12%	4932	18%
	25	55631	20%	80177	17%	3568	19%	12630	12%	5486	22%
	50	61001	21%	87406	17%	3947	16%	13500	11%	5881	24%
	100	66324	21%	94532	16%	4323	12%	14334	11%	6264	27%
	500	78738	21%	111016	15%	5195	3%	16183	10%	7130	34%
Average (2-100)	mid century		11%		9%		20%		8%		12%
Average (2-100)	late century		19%		16%		19%		12%		20%

Summary by Quantile

Mid Century (2016-2060 vs 1970-2015)

	Return Period	Average	Minimum	Maximum
2016 - 2060	2	14%	6%	23%
	5	17%	9%	27%
	10	16%	9%	27%
	25	13%	6%	26%
	50	11%	2%	24%
	100	8%	-2%	21%
	500	2%	-11%	19%

Late Century (2055-2099 vs 1970-2015)

	Return Period	Average	Minimum	Maximum
2055 - 2099	2	17%	11%	24%
	5	19%	10%	24%
	10	19%	10%	24%
	25	18%	10%	26%
	50	17%	8%	28%
	100	16%	3%	29%
	500	13%	-9%	34%

APPENDIX C –CONTEXT FOR CURRENT CLIMATE CHANGE PREDICTIONS

Putting the new Chehalis DHSVM results in context

Guillaume Mauger, Larry Karpack

Over the past five years, the potential for changing flood flows in the Chehalis Basin has been assessed several times using both available literature and basin specific studies (Snover et al. 2014, Salathé et al. 2014, Mauger et al. 2016, and WSE 2019). Reporting of the results of these studies, as summarized in the table and figure below, may cause some confusion because the results differ substantially in terms of the projected change in peak flows. There are a number of differences in the data and methods used in these studies that help explain these differences in results. The purpose of this document is to briefly summarize the differences among these studies in order to provide some context for interpreting the latest results described in Chehalis River Basin Hydrologic Modeling Memorandum (WSE 2019).

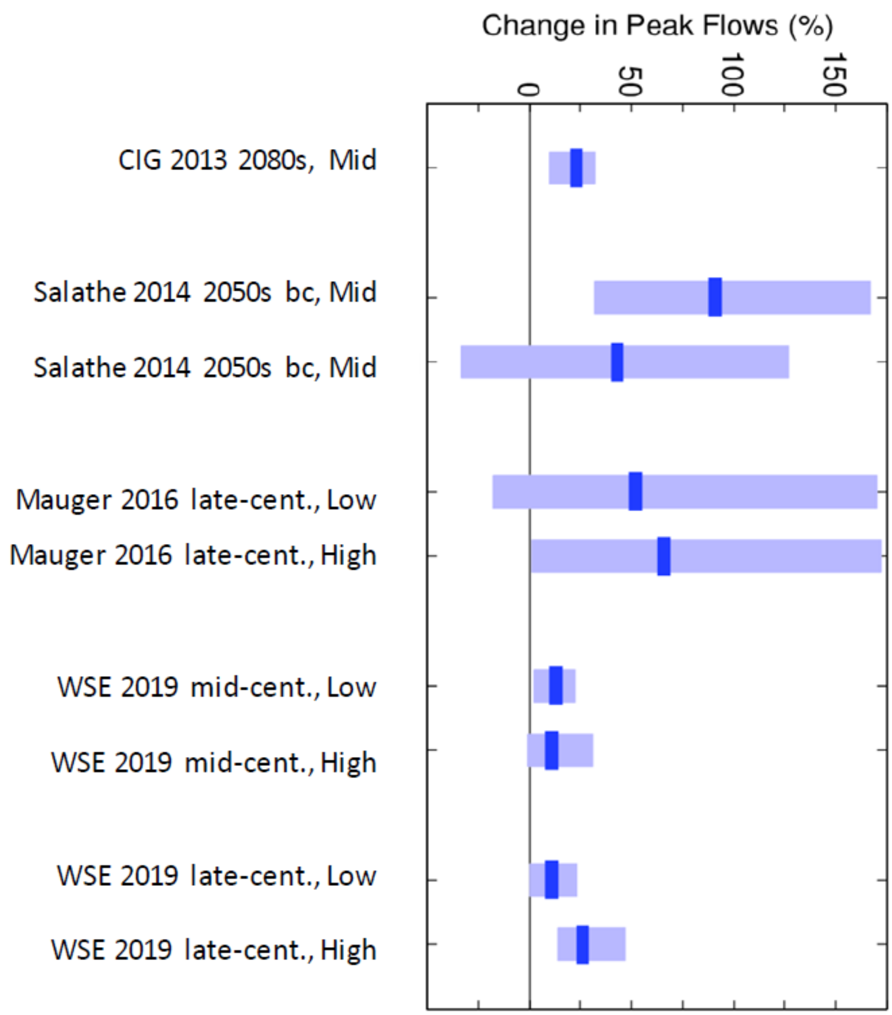

Figure 1. Summary of flood projections for the Chehalis River Basin. The figure shows the stated estimate, and range, for each of the four studies.

Each Study Has Different Ingredients

Hydrologic change projections are produced by first obtaining global climate model projections, then “downscaling” those projections to spatial scales that can be used for hydrologic modeling. These downscaled climate projections are then used to simulate streamflow using a hydrologic model. Each of these steps includes choices about which data to use, and involves data, tools, and approaches that are continually evolving over time. Some key differences in the past studies are summarized in the table and text below.

CIG 2013: The first climate change projections that were cited for the Chehalis River were based on an older set of global climate models (Meehl et al. 2007), a statistical approach to downscaling climate model projections, and uncalibrated results from the coarse-scale Variable Infiltration Capacity (VIC) hydrologic model. Subsequent work has shown that statistical downscaling does not accurately capture changes in heavy precipitation events – the principal driver of changing flood risk in the Chehalis basin (Salathé et al., 2014). Since the VIC model was not calibrated for the Chehalis River, results were included for all rain-dominant watersheds in the Pacific Northwest. Finally, this study used 30-year averaging periods to estimate changes, which may not be sufficient to produce robust estimates of the 100-year flood statistic.

Salathé 2014: This second set of projections replicated the approach of CIG 2013, but used a dynamical downscaling approach. As in CIG 2013, an uncalibrated version of the VIC hydrologic model was used. The results showed evidence for an improvement in accuracy over the statistically downscaled projections (see Dulière et al. 2011), but were limited in two ways: (1) the projections were based on just one global climate model, which may not be representative of the larger set of models, and (2) subsequent work has shown that the bias-correction applied to the dynamically downscaled climate data may result in substantial overestimates in the projections (Mauger et al. 2016). Finally, the Salathé 2014 projections only extended through 2070 as opposed to the three other studies, all of which continue through 2100.

Mauger 2016: This study improved on the previous two estimates by using an updated set of global climate model projections and improved streamflow simulations including the development of a finer-scale Distributed Hydrology Soil Vegetation Model (DHSVM). Unfortunately, the DHSVM model developed for this study was not calibrated to observed flows and the results of the DHSVM modeling were not found to be reliable. Therefore, final climate projections produced in 2016 were made using the coarser scale VIC model. Also, although the 2016 study explored using dynamically downscaled meteorological data, the dynamical downscaling was limited to just two global climate models and did not extend past 2070. As a result, final climate change projections in 2016 were made based on VIC modeling of statistically downscaled climate projections from ten different GCMs. As noted above, recent studies have found that statistical downscaling is not as robust as dynamical downscaling, particularly in basins such as the Chehalis where changes in extreme precipitation are the primary driver of increasing flood quantiles.

WSE 2019. The current study improved on Mauger et al. (2016) by (1) using new dynamically-downscaled projections, (2) calibrating the DHSVM model, and (3) using an hourly time step as opposed to only considering changes in daily precipitation. This study was the first time that dynamically downscaled simulations were used in both model calibration and to develop climate change projections: an important methodological improvement that was lacking in Salathé et al. (2014). The primary limitation of this study is the lack of sufficient climate projections to reliably estimate the range among projections: two global climate models is simply not sufficient to do this. In addition, model calibration was complicated by shortcomings in the dynamically downscaled historical meteorological data and challenges in the application of DHSVM to such a large basin.

Table 1. Summary of methods and projections for changing flood flows on the Chehalis River. For WSE 2019, the projections for the late 21st century are highlighted in bold.

	CIG 2013	***Salathé 2014***	***Mauger 2016***	***WSE 2019***
Global Climate Models	10	1	10	2
Greenhouse Gas Scenarios	Medium (A1B)	Moderate	**Low**, Moderate, **High**	Low, High
Downscaling Approach	Statistical	Dynamical	**Statistical** Dynamical	Dynamical
Hydrologic Model	VIC	VIC	**VIC** & DHSVM (uncalibrated)	DHSVM (calibrated)
Time Step	daily	daily	daily	hourly
Post-Processing	30-years, GEV	bias-corr., 30-years, GEV	55 or 60-years, LP3	45-years, LP3
Periods for Comparisons	1970-1999 v 2070-2099	1970-1999 v 2040-2069	1951-2005 v 2040-2099	1970-2015 v 2016-2060 v 2055-2099
Results (100-year flood)	+18% (11-26)	+91% (32-167)	RCP 8.5 +66% (1–172) RCP 4.5 +52% (-18-170)	RCP 8.5 (11%, 26%) RCP 4.5 (13%, 11%)

Evaluating the Latest Results

The new projections match up well with global climate model projections of changes in heavy rain events. From Mauger et al. (2014):

> *"Global models project that the heaviest 24-hour rain events in western Oregon and Washington will intensify by +22%, on average, by the 2080s (2070-2099, relative to 1970-1999)."*

Projections from each of the 10 global models range from an increase of +5 to +34% in 24-hour precipitation intensity. These projections, a regionally-averaged result covering all of Oregon and Washington, are very similar to the results of WSE (2019) for the Chehalis River.

It is important to note several limitations to this comparison: (1) a given increase in precipitation might not result in the same increase in flooding, (2) the 100-year flood may not change by the same amount as the heaviest 24-hour precipitation event in an average winter, and (3) the average change for Oregon and Washington may not be the same as that projected for the Chehalis River basin.

There are also several reasons that the latest results for the Chehalis River basin may change with further study. First, the results are based on just two global climate models. This is not enough: studies generally indicate that 6-10 different model projections are needed in order to develop a representative estimate of the mean and range among projections. Second, there are outstanding questions about how to address biases in the meteorological data and the optimal way to configure and calibrate the hydrologic model; both could be improved with additional investigation.

Conclusions

The latest results for the Chehalis River basin are an improvement over previous studies. Previous studies included results from outside the Chehalis River basin, older global climate model projections, a less reliable statistically-based approach to downscaling, a coarser hydrologic model, and no hydrologic model calibration. Each of these issues is addressed in the current study. The current methods could be further refined, but they are nonetheless an improvement over previous work.

The new flood projections are consistent with global model projections of changes in heavy rainfall (22% increase in the heaviest 24-hr events, by the 2080s). The previous projections (Mauger et al., 2016) projected an average increase of 66% for peak flows in the Chehalis River basin. Even if flooding increases more rapidly than precipitation, it is difficult to reconcile an increase of this magnitude with a 22% increase in precipitation. In addition, the Mauger et al. (2016) study was based on statistical downscaling, an uncalibrated hydrologic model, and only evaluated changes in daily streamflow extremes as opposed to hourly in the latest study. As a result, we consider the new projections (11-26% increase in peak flows, by the late 21st century), to be more plausible.

One near-term opportunity for improving on these projections would be to increase the number of climate projections considered. Current modeling at UW is nearing completion, which would provide additional dynamically downscaled projections. These could be used to obtain a total of at least six flood projections as opposed to the two that are currently available. In addition to this improvement, future work could further evaluate and address biases in the climate projections and improve on the hydrologic model calibration.

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