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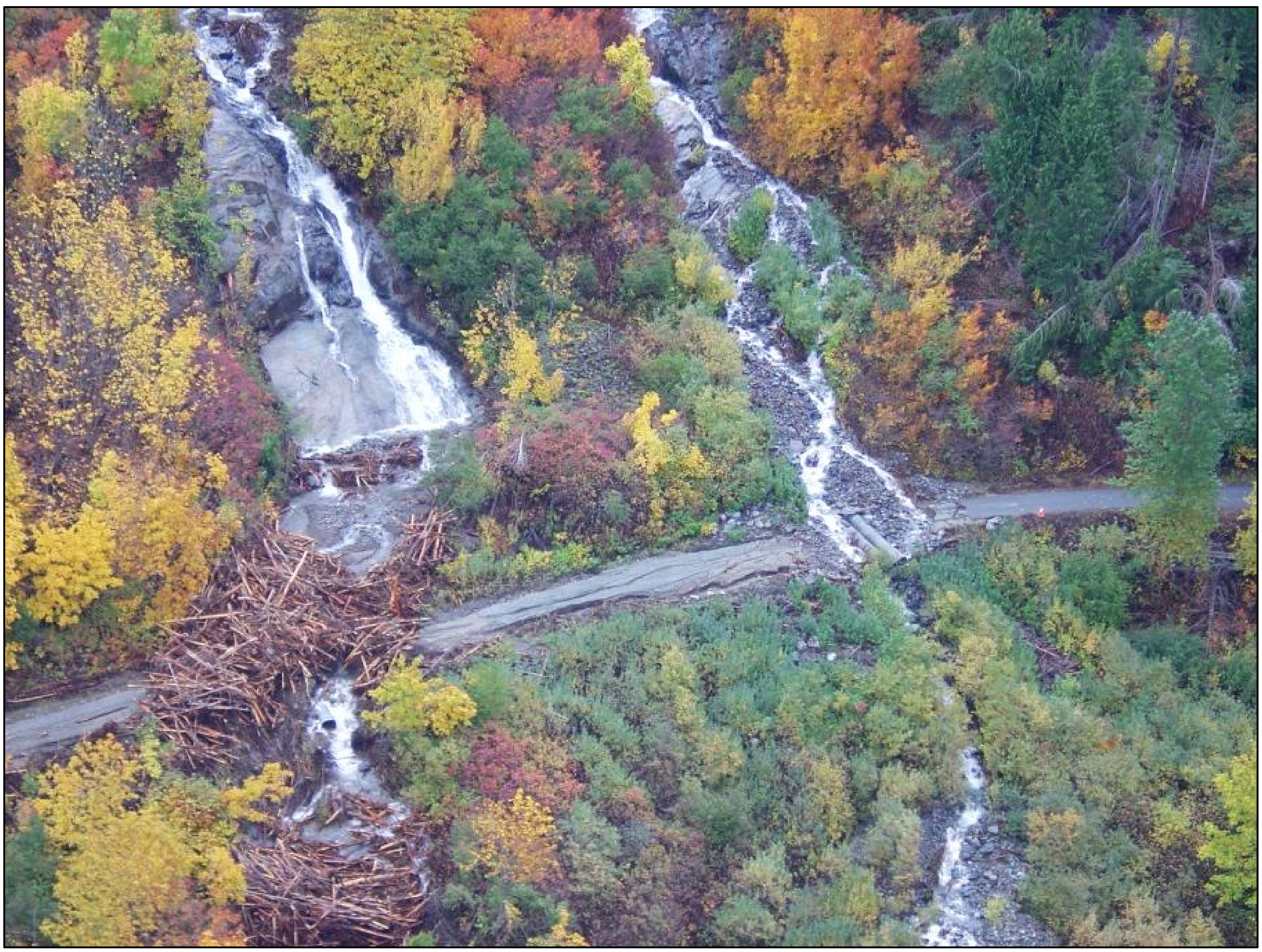
Developing a GIS-based Geospatial Decision Support Tool for Assessing Climate Change Impacts on Flood Risks in Northern Cascadia Road Networks

Natural Resource Report NPS/NOCA/NRR—2018/1808



ON THIS PAGE

Photograph of hikers on Cascade River Road in North Cascades National Park facing a damaged road from culvert failure during a storm in August 2013.

Photograph courtesy of the National Park Service

ON THE COVER

Aerial photograph of the damaged Cascade River Road in North Cascades National Park in October 2003.

Photograph courtesy of the National Park Service

Developing a GIS-based Geospatial Decision Support Tool for Assessing Climate Change Impacts on Flood Risks in Northern Cascadia Road Networks

Natural Resource Report NPS/NOCA/NRR—2018/1808

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Executive Summary

Changes in temperature and precipitation patterns associated with changing climate have direct effects on the hydrologic system that impact transportation systems. Peak flows are particularly challenging to the integrity of road segments that intersect streams. This report evaluates four possible approaches for estimating peak flows in the future to assess impacts and manage culvert stream-crossing structures within North Cascades National Park (NOCA). Because streamflow measurements are only performed at a few locations within NOCA and on large streams where culverts are too small for use as road or trail crossings, these measurements are not appropriate for predicting peak flows in small streams where culverts are located. Thus, hydrologic modeling provides an approach to estimating streamflows in the future at small scales appropriate for culverts.

This study found that information on NOCA culvert locations and conditions is insufficient to inform NPS managers interested in adapting transportation systems to changing climates. Thus, this report describes tools developed to inventory culverts and document culvert conditions. A data sheet, geospatial database, and mobile app were developed to help increase the culvert information retained by the park. This study also explored several methods to estimate future peak streamflow based on hydrologic modeling using the Variable Infiltration Capacity (VIC) macro-scale hydrology model, which was previously run for the study area. A potential limitation of the VIC model is the *daily* scale data used to derive peak flows estimates, which results in lower peak flows estimates than when using observations based on *instantaneous* (i.e., 15 minute) data. However, this limitation can be accounted for with a correction factor that scales the daily-based estimate with the instantaneous-based estimate. The major value of the VIC model lies in its ability to capture hydrologic processes, such as evapotranspiration and snowmelt, that will change in the future as temperatures warm. Therefore, peak flow estimates derived from the VIC model provide a mechanism to understand how these changing processes will alter peak flows in the future, which is important for designing and operating transportation infrastructure over the long term.

The VIC model can be used in combination with existing streamflow estimation tools that are based on historical climatology. StreamStats, a USGS online tool, is currently used by managers to estimate peak flows on ungauged streams. However, it does not take into account future change in climate and its effect on stream flow. An approach was developed to use the changes in peak flow estimated by VIC, represented as a ratio of future to historic peak flows, to adjust the estimated peak flows provided by StreamStats. Throughout the park, the future-to-historic streamflow ratio is increasing for higher peak flows (e.g., 100-year flows or Q100), with greater increases later in the century. This indicates expected increases in peak flows in the future. At lower peak flows, some areas on the eastside of the park may see declines in mean annual flows (Q2) in the future, primarily because of reduced snowpack. A simple Excel spreadsheet tool was developed to quickly adjust estimates of peak flows from StreamStats using the VIC model future projections of streamflow. The tool provides five different peak flow return periods between 2 and 100 years (i.e. Q2, Q10, Q25, Q50, and Q100) based on climatology from ten different future climate scenarios modeled by Global Climate Models for both the 2040s and 2080s, thus disclosing future flow uncertainty. This tool can be used in the design of culvert sizes to accommodate future channel flows, to assess areas with higher risk of damage from greater changes in peak flows, and in prioritizing culvert inventories and maintenance.

Acknowledgments

This project was conducted through the Pacific Northwest Cooperative Ecosystem Studies Unit, with funding support provided by the National Park Service in Task Agreement P13AC00706. Project management was provided by Dr. Regina Rochefort of the National Park Service. The study was directed by Dr. Erkan Istanbulluoglu and was carried out by his graduate students Ronda Strauch and Zhuoran Duan, at the University of Washington (UW). Computer code assistance in data processing and analysis was provided by UW students Jiawei He and Sai Siddhartha Nudurupati. University of Idaho student Kelly Purnell explored advanced geospatial analyses. Thoughts on data interpretation and the analysis approach, as well as the Excel tool template, were provided by Ingrid Tohver and Se-Yeun Lee of University of Washington's Climate Impacts Group. Technical reviews were provided by Jon Riedel, Michael Larrabee, and Christopher Lauver. We are grateful to Angelina Nguyen for formatting this report for publication.

Introduction

A multi-agency science-management partnership was established in 2011 called the North Cascadia Adaptation Partnership (NCAP) (Raymond et al. 2014). This partnership was established to increase awareness of climate change, assess vulnerabilities to resources, and incorporate climate change adaptation ideas into the current management of National Park Service (NPS) and US Forest Service (USFS) lands. During a partner workshop, the lack of comprehensive data on culverts was identified as a critical information gap vital for adapting management of transportation systems to changing hydrologic regimes where roads intersect streams. Hydrological modeling studies that use projected climate change scenarios from Global Climate Models (GCMs) have shown that the 21st-century climate may produce more extreme floods, earlier spring flows, and reduced summer low flows in the Pacific Northwest (PNW) (Elsner et al. 2010; Mote and Salathé 2010). Culverts that are used to convey streamflows under roads or trails will be at an increased risk of inundation (i.e., flooding) and failure under the growing flood extremes with climate change (e.g., Fig.1). Culvert performance affects both transportation and stream system functions (e.g., fish passage; Wilhere et al 2017). However, local data on culverts installed on NPS and USFS lands are limited and less detailed compared to larger and more visible infrastructure such as bridges.

Figure 1. Repair of Boston Creek culvert on Cascade River Road in August 2013. Photo courtesy of the National Park Service.

The long-term success of culverts during their operational lifespan primarily depends on the following factors: (1) an accurate prediction of flood flows at culvert sites, and (2) the ability of culverts to pass design flows and associated sediment and debris. A standard procedure to select culvert sizes is based on the estimated streamflow discharge (e.g., cubic feet per second) of a flood event with a return period of 25 years (Q25) to 100 years (Q100), conventionally derived from historical streamflow records. The 100-year flood is the annual maximum streamflow exceeded with a 1% probability in any year, or with a chance of 1 in 100. The changes in the frequency and magnitude of extreme events under changing climate are not represented or utilized in the selection of flood frequency. Physically-based hydrology models overcome the limitations of methods based on historical measurements of streamflow by incorporating changes in the climatic (past and future) and environmental variables (e.g., soils and vegetation) in distributed streamflow predictions. Thus, they are suitable for predicting future peak flows at culvert sites. Future peak flows can be used with a detailed dataset of culvert conditions, including culvert type, dimensions, placement, and surrounding environmental conditions (such as vegetation, stream conditions, sediment size, landforms), to determine the culvert sites that have a high risk of failure, need replacement and maintenance, or are relatively resilient to changing hydrologic regimes.

The project described in the report was initiated by the NPS and the University of Washington to address the challenges the NCAP identified with managing culverts in a changing flooding regime. We used North Cascades National Park Service Complex (NOCA) as our study area to address project goals:

1. Determine the peak flows from simulations of historical and future streamflow by the Variable Infiltration Capacity (VIC) hydrologic model driven by climatology from multiple GCMs.
2. Assess methods for estimating peak flows in the future and create a simple tool for considering future peak flows in transportation management.
3. Review existing culvert information maintained by the NPS and develop recommendations for improving data collection.

Estimating Peak Flows Under Future Climate

Hydrologic Data and Peak Flow Distribution

Numerous methods have been developed for estimating peak flows (see Mastin et al 2016); however, projecting peak flows in the future under a changing climate requires the use of hydrologic models run with future climatology. Changes in hydrology in the future are driven mainly by increasing temperature and associated evapotranspiration, decreasing snowpack, and more variable and intense precipitation (Tohver et al. 2014; Snover et al. 2013; Elsner et al. 2010). These changes in hydrology are instrumental to the long-term functioning of the transportation network (Wilhere et al. 2017; Hayhoe et al. 2015).

The aim of this project was to use existing, readily available data rather than generate new data, which is computationally and time intensive. Therefore, future projections (i.e., future forecast) of stream flow were acquired from the *Pacific Northwest Hydroclimate Scenarios Projec*t developed by an interdisciplinary research group associated with the Climate Impacts Group at the University of Washington (Hamlet et al. 2013). This calibrated dataset was selected because it was developed specifically to support comprehensive assessments, planning, and adaptation in Washington. Additionally, this dataset has been and continues to be used in numerous peer reviewed studies throughout the region (Strauch et al. 2018; Raymond et al. 2014; Tohver et al. 2014; Elsner et al. 2010). These data are at a spatial resolution of 1/16th degree (~34 km^2) based on statistically downscaling approaches from the ten best-performing GCMs for this region forced by the A1B greenhouse emissions scenario (http://cses.washington.edu/cig/data/), which aligns with the current emission trajectory (Nakićenović and Swart 2000). Hydrologic data were obtained from applications of GCM meteorological data as input into the Variable Infiltration Capacity (VIC) macroscale hydrological model (Liang et al. 1994). The VIC model acts as a translator between changes in climate and hydrologic effects on river flows, snowpack, soil moisture, and other ecosystem processes (Littell et al 2011, Elsner et al. 2010, Hamlet 2010, Mote & Salathé 2010).

Details on the climate dataset used in this study can be found in Hamlet et al. (2013); however, a brief synopsis is provided here. Daily precipitation, runoff, and baseflow data from the VIC simulation are available for historical climate and projected climate in the 2040s (2030-2059) and 2080s (2070-2099) at 1/16th degree grid cells. Historical baseline model simulations where generated from temperatures and precipitation acquired from station observations covering 1916 to 2006. The VIC simulation was calibrated and validated using naturalized streamflow measurements in the Columbia River Basin and was found to reasonably match observational flow statistics (e.g., mean and high flows), with slight improvements at finer scale calibration (Hamlet et al. 2013; Wenger et al., 2010). However, watershed with significant streamflow contributions from glaciers and "deep" groundwater may show divergence between simulated and natural streamflows (Lee et al., 2016; Hamlet et al. 2013). Future projections of runoff and baseflow were generated using the hybrid-delta statistical downscaling approach, which includes spatial variability in temperatures and precipitation from each GCM (Hamlet et al. 2013). About 113 VIC grid cells cover the 2,757 km^2 area of NOCA (Fig. C4).

Hydrologic projections from the VIC model provide daily streamflow estimates from which annual maximum daily flows can be extracted. The annual peak flow is defined as the maximum daily or instantaneous (15 minute) flow occurring in a water year (Oct. through Sept.). Annual peak streamflows range from flows that barely exceed the natural stream banks to flows that inundate the floodplain.

Streamflows can be used to develop return period or the recurrence interval of streamflow magnitudes of interest, which are often used to design culverts or examine culvert capacity. For example, the 100-year flood is the annual maximum streamflow exceeded with a 1% probability in any year, or with a chance of 1 in 100. This is often symbolized by Q100. Mean annual flow (Q2) is the flow that typically occurs with a 50 percent chance each year. Peak flows for five different return periods (i.e., Q2, Q10, Q25, Q50, Q100) were estimated from the daily-time-step VIC simulated annual peak streamflows for each of the 280 grid cells (see Fig. C4) in and around NOCA for historical conditions and ten future modeled conditions, plus an ensemble, at two different future time periods (i.e., 115 different flow magnitudes). The ensemble (e.g., average) of peak flow data was created from the ten GCMs and integrates uncertainty in streamflows derived from uncertainties in different temperature and precipitation provided by different GCMs (Tohver et al. 2014; Hamlet et al. 2013). The probabilities of exceedance for peak flows (i.e., probability of exceeding a particular flow) were determined at each grid cell by four different methods: log-Pearson III, Gumbel, Generalized Extreme Value (GEV), and Log Normal. The return period for peak flows is the inverse of this probability of exceedance. A figure and table (Fig. 2, Table 1) were created to summarize these probability distributions for each grid cell.

To determine which extreme value distribution to use for estimating peak flow, an examination of L-moments, which is a method of summarizing the statistical properties of a dataset based on linear combinations of the ranked data, was performed for a sample of grid cells (Wang, 1997; Hosking 1990). L-moments were calculated for ten grid cells randomly selected from the VIC model simulations for historic and future (*Echam 5* GCM) simulations for two time periods. The first and second L-moments estimate the dataset mean and variance, while the third and fourth L-moment estimate the skewness and kurtosis (i.e., distribution shape) of the dataset. L-moment ratios can be used to guide distribution selection by plotting L-Skewness ratio (3^{rd} L-moment/2^{nd} L-moment) by L-Kurtosis ratio (4^{th} L-moment/2^{nd} L-moment) (Stedinger et al. 1992). A plot of these ratios for the randomly selected grid cells cluster around several distributions, indicating that all were relatively similar in estimate peak flow values (Fig. 3). Additionally, no distinct differences between simulations were evident.

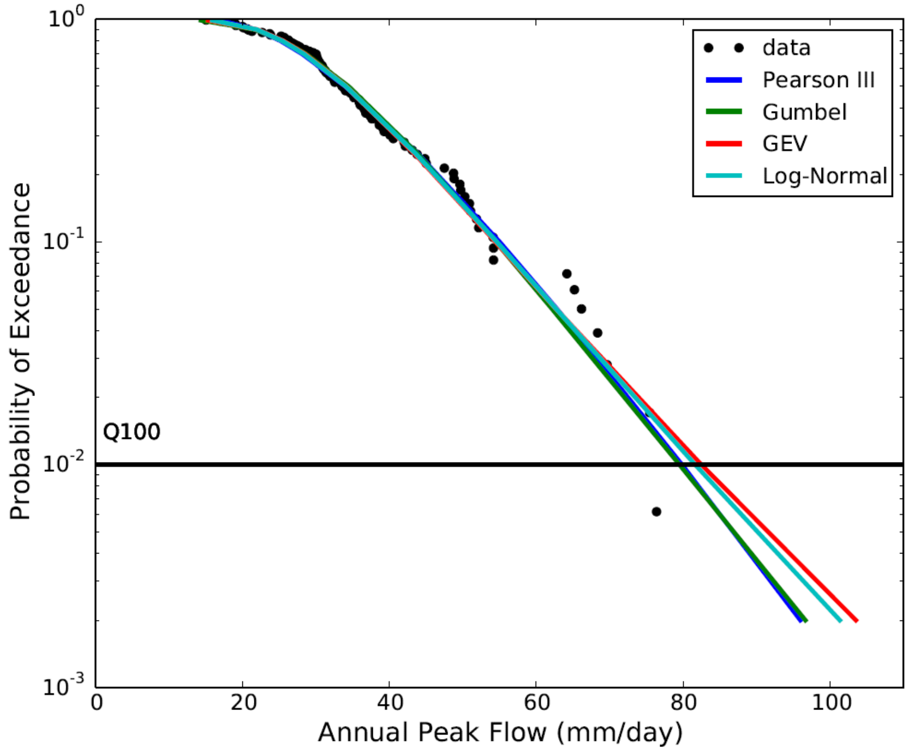


Figure 2. Probability of exceedance (1/return period) estimated by four different distributions for one grid cell located at 48.46875 latitude, -121.21875 longitude (cell 87 on Fig. C4) based on VIC simulation under historical (1916-2006) conditions. Horizontal line represents the probability of flows with a 100 year return period.

Table 1. Estimated peak flows in mm/day estimated by four different distributions for *one* grid cell located at 48.46875 latitude, -121.21875 longitude (see Fig. C4 for cell #87 location).

Return Period	Log-Pearson III	Gumbel	GEV	Log Normal
2	34	34	34	34
10	55	54	54	54
25	65	64	65	65
50	72	72	73	73
100	79	79	82	81

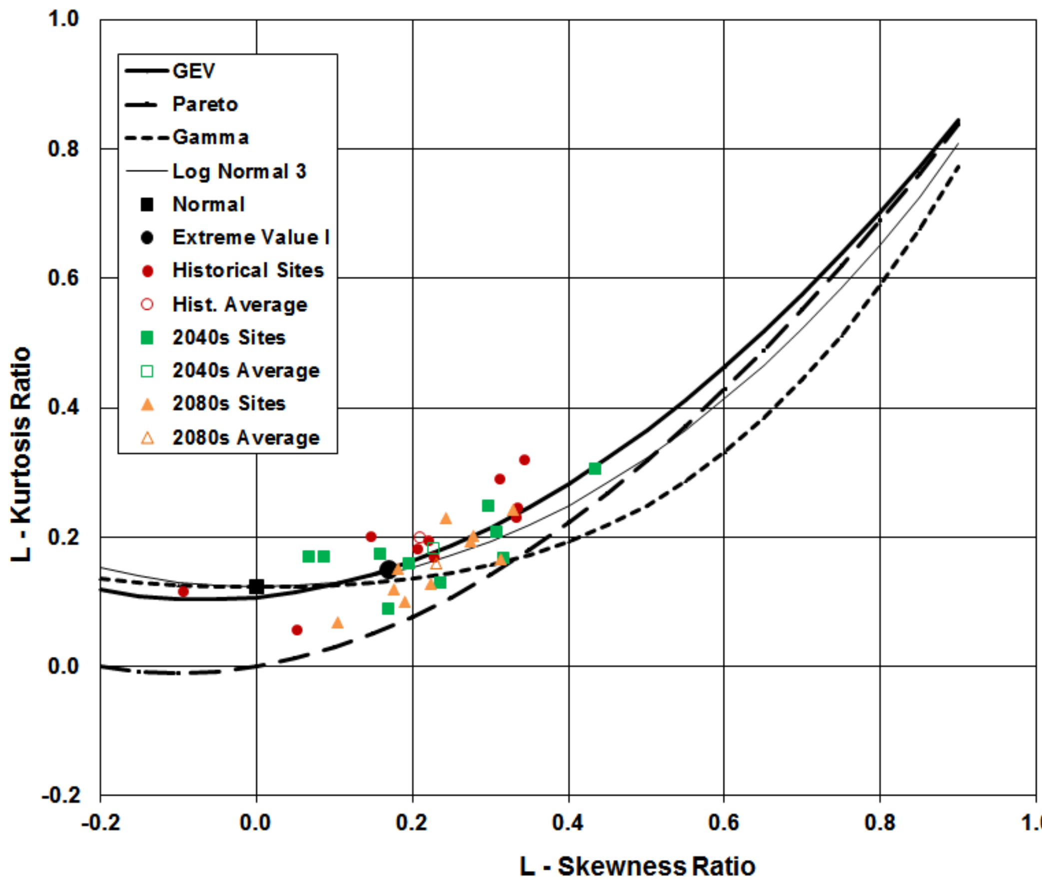


Figure 3. L-moment diagram used to select an extreme value distribution. Plotted values are the calculated L-moment ratios for VIC model simulations for historic and future (*Echam 5* GCM) 2040s and 2080s simulations, as well as the average of the points for each time period (open symbols).

Correction of Model Streamflows with Observed Flows

When compared to historical measurements of streamflow, the VIC model may underestimate peak streamflow because of errors in model precipitation forcing data, such as localized storms not captured in precipitation gages but recorded by streamflows gages, or the model inadequately represents saturation patterns under high precipitation. Therefore, the future streamflows were adjusted using two different procedures discussed in detail below. The first procedure creates relationships between simulated and observed streamflows while the second approach uses the VIC simulated streamflow to adjust the streamflow derived from the U.S. Geological Survey (USGS) StreamStats tool (http://water.usgs.gov/osw/streamstats/). This tool is often used by managers to calculate the magnitude of peak streamflow in watersheds of interests. A comparison of these approaches is discussed below in *Comparison of Methods and Results*.

Modeled Streamflow Adjusted with Observational Relationships

Using historical streamflow measurements at USGS stream gages, observed annual maximums were compared to the VIC simulations. For watersheds within NOCA, USGS maintains several stream gages that provide daily and instantaneous streamflow for three watersheds examined in this study: Cascade River, Thunder Creek, and Stehekin River (Table 2; Fig. 4). Simulated runoff plus baseflow from the VIC model were routed to an outflow location near the stream gages of these watersheds to provide simulated streamflows that could be compared to observed streamflows at the watershed scale.

Table 2. Watersheds examined in North Cascades National Park Complex and their basic traits.

Watershed	USGS Code	Latitude Longitude	Drainage Area Km^2 (mi^2)	Elevation of Gage Meters (ft)
Cascade River	12182500	48°31'35" -121°24'51"	480 (185)	101 (330)
Stehekin River	12451000	48°19'47" -120°41'26"	885 (342)	335 (1,099)
Thunder Creek	12175500	48°40'22" -121°04'18"	278 (107)	372 (1,220)

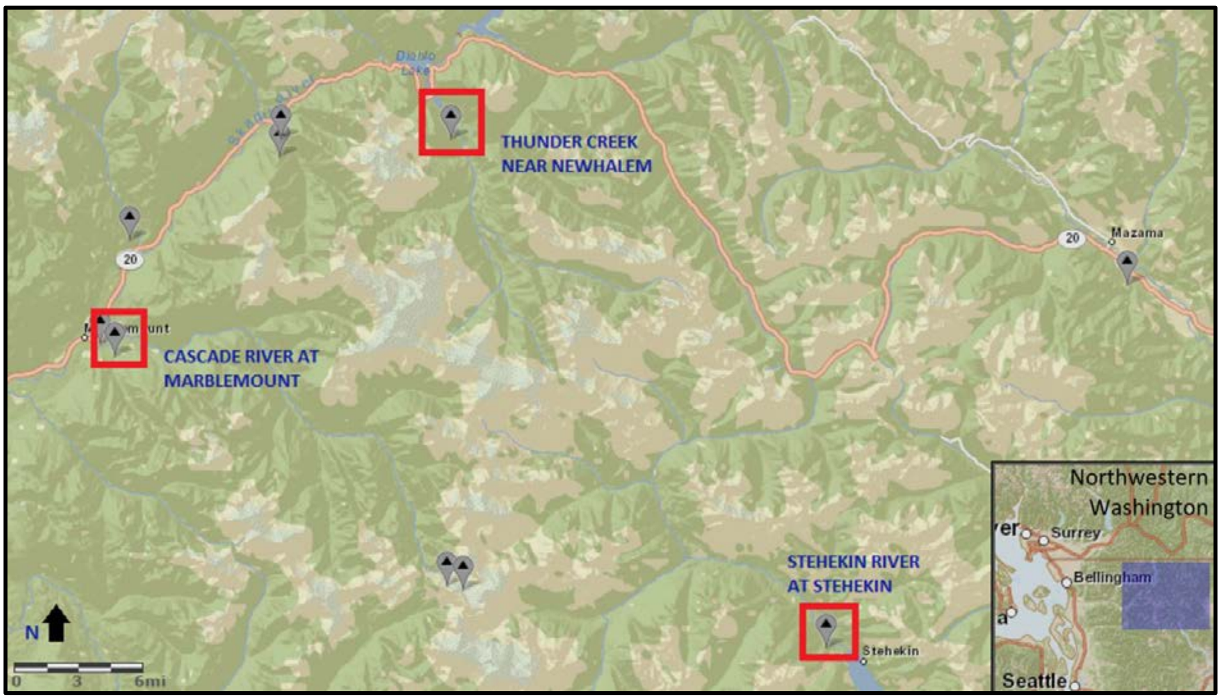


Figure 4. Location of USGS stream gages with peak streamflow data in North Cascades, Washington. Source: http://maps.waterdata.usgs.gov/mapper/index.html.

Streamflows were used to generate annual peak flows using the log-Pearson Type III distributions approach, which is commonly used by federal agencies as recommended by USGS Bulletin 17 (Stedinger et al. 1992) and was found to be suitable for multiple regions in Oregon (Campbell 1981). Routed VIC simulated streamflow and observed streamflow return periods derived from the same distribution are compared in Figure 5. Streamflows for a given return period are lowest for VIC simulated daily streamflow and highest for observed instantaneous streamflow. Additionally, the estimates of various peaks by VIC are more compact (i.e., narrow range of peak flows) than the different peak flows estimated from observational data (Fig. 6). Q100 based on observed *instantaneous* data is two to three times greater than Q100 based on VIC modeled *daily* flows. This emphasizes the value of instantaneous streamflow data in providing the highest flows that a culvert might experience during a day. For most flow levels, Thunder Creek had the lowest peak flows while Stehekin River had the highest, commensurate with increasing watershed area, although these basins also vary in geology and vegetation cover. However, Q50 and Q100 based on instantaneous data were highest for Cascade River, which may be associated with the more western location of this watershed in relation to storm direction (Fig. 6). Because VIC modeled daily flows underestimated peak flows from observations, we sought an adjustment of these streamflows toward the instantaneous streamflows magnitudes using observational data so that the VIC modeled streamflows could be used in future time periods.

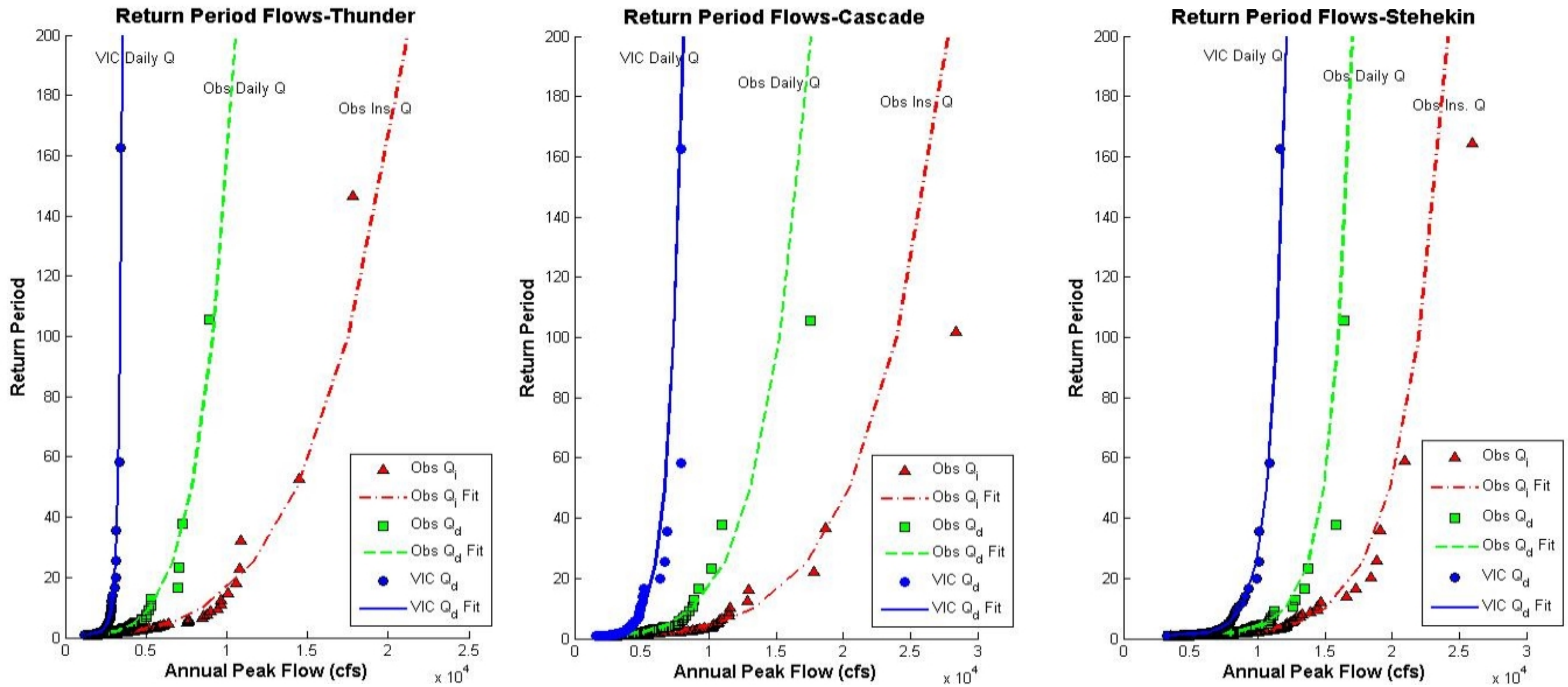


Figure 5. Return period (years) of historical annual peak of routed VIC daily simulated streamflow (Q_d^v), observed annual peak of daily mean streamflow (Q_d^o), and observed annual instantaneous peak streamflow (Q_i^o) for Cascade River, Thunder Creek, and Stehekin River watersheds. Data are fitted (curved lines) with log-Pearson Type III distributions.

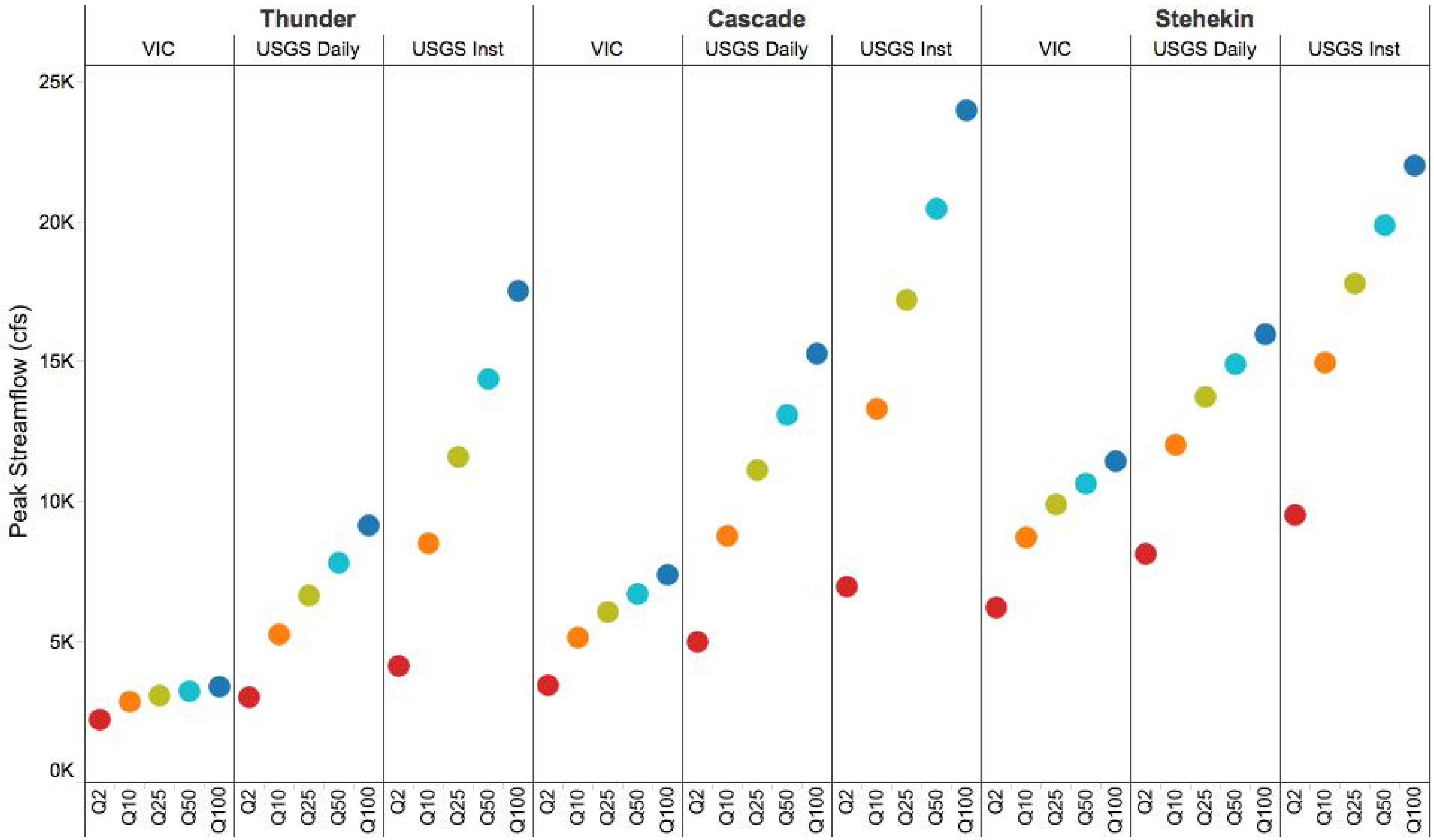


Figure 6. Estimated peak streamflows with return periods of 2 to 100 years (i.e. Q2, Q10, Q25, Q50, and Q100) based on fit as described in Figure 3 for three watersheds in North Cascades National Park Complex.

The USGS stream gages in NOCA are located where streamflow is higher in magnitude than where culverts would typically be located. Therefore, our initial approach was to derive flows at a culvert location upstream from these gages using a synthetic dimensionless unit hydrograph derived from the gage observations at the watershed scale. Cascade River watershed was selected as a trial watershed on which to develop this unit hydrograph. Initially, the runoff volumes were separated from the baseflow volumes (i.e., flows without storm contribution) for selected storms within the observed streamflow record to identify the response (i.e., hydrograph or flow versus time) in streamflow for a given storm event. This information was used to derive a 1-hour synthetic hydrograph (Nathan and McMahon 1990; Sujono et al 2004). A synthetic unit hydrograph integrates components of the watershed characteristics such as area, slope, and vegetation cover; therefore, these basin characters can be reflected in estimations of streamflow at an outlet.

Due to limitation of available precipitation and streamflow data at smaller watershed scales, it was challenging to use this approach directly for obtaining streamflow response to storms in small watersheds necessary for culvert design. However, examination of the streamflow observations revealed a direct linear relationship between the observed daily streamflow and the observed instantaneous streamflow at the larger watershed scale (Fig. 7). Observed annual maximum *instantaneous* streamflows typically exceed or are equal to observed annual maximum *daily* streamflows (Fig. 6). Based on a linear relationship, observed annual maximum *instantaneous* streamflow ranged from 1.2 to 1.5 times higher than the corresponding *daily* mean streamflow. This relationship provided the opportunity to develop an adjustment of the VIC simulated daily streamflows using the observed daily and instantaneous streamflows. VIC simulated daily streamflow routed to the watershed outlets were used to identify the maximum streamflows in each water year (October 1 to September 30) and these *modeled* annual daily peak streamflows were linearly related to *observed* annual daily peak streamflow (Fig. 8). Routed flows gather the flow from "upstream" cells contributing to the flow in a particular cell and provide better estimates of streamflow magnitude by including the cells in a network draining to a location of interest. Using these derived relationships, VIC simulated daily streamflows could be scaled to estimate instantaneous streamflows (Fig. 9). Linear equations were developed for each of the three watersheds and all three watersheds combined to estimate simulated instantaneous streamflow by transforming VIC simulated daily flows based on linear relationships with observed streamflows, assuming that the line passed through the origin (Table 3).

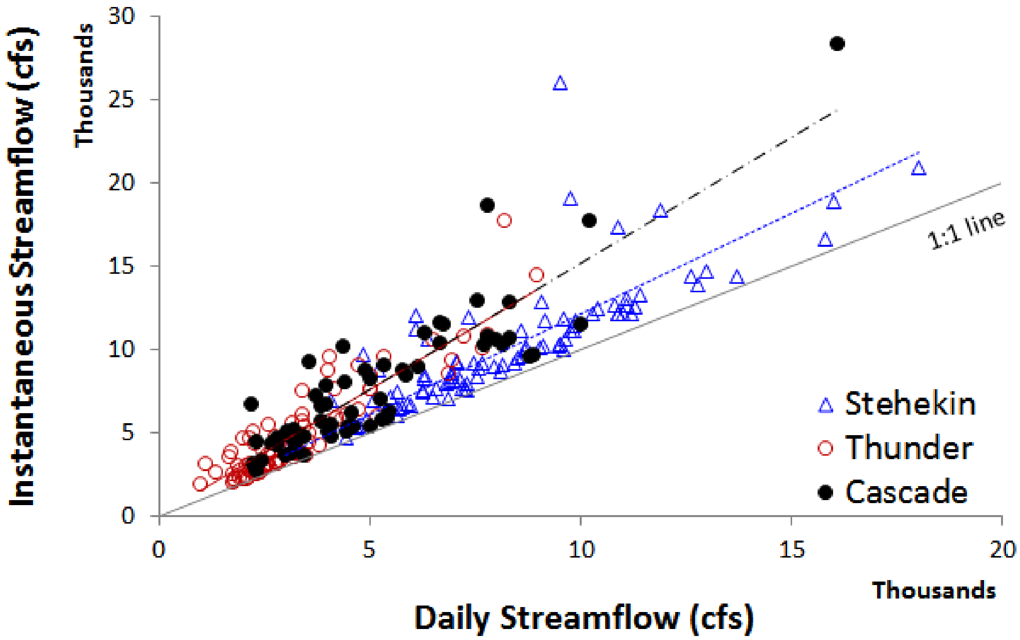


Figure 7. Relationship between observed annual instantaneous peak flows and corresponding daily mean flow at Cascade River, Thunder Creek, and Stehekin River watersheds. Data from USGS stream gages. Linear trend lines shown for each watershed and 1:1 line shown as solid line.

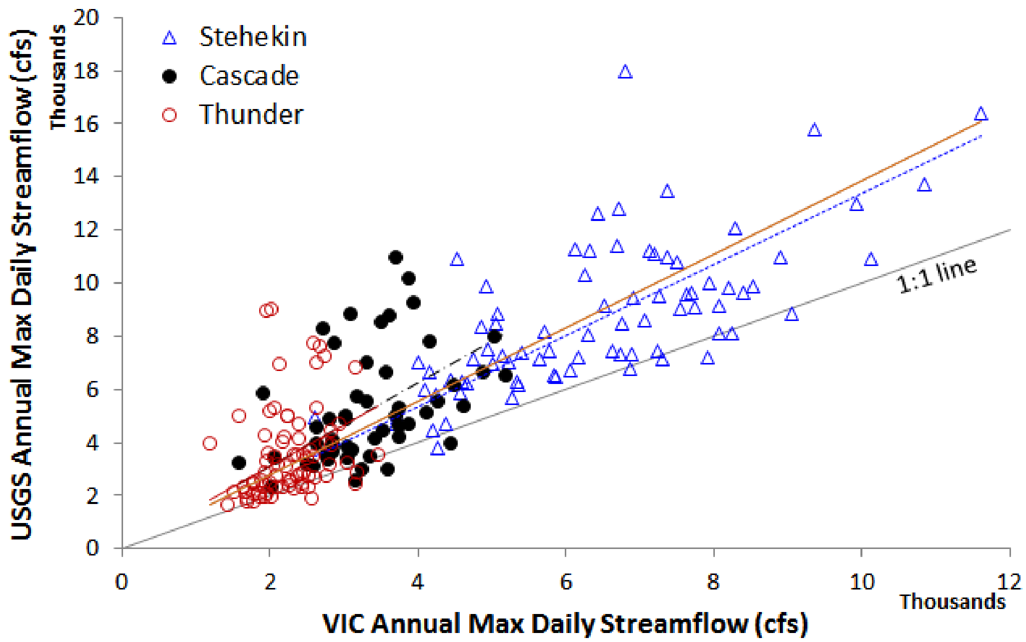


Figure 8. Relationship between USGS annual maximum daily flows and corresponding VIC simulated annual maximum flow for the same year at Cascade River, Thunder Creek, and Stehekin River watersheds. Linear trend lines shown for each watershed and 1:1 line shown as solid line.

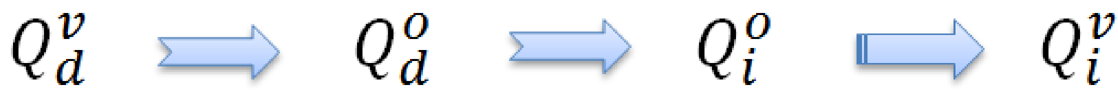


Figure 9. Flow diagram of transforming VIC simulated daily streamflows (Q_d^v) into instantaneous (Q_i^v) streamflows based on observed daily and instantaneous streamflow (Q_d^o *and* Q_i^o) relationships.

Table 3. Linear regression equation and r² values for transforming VIC simulated daily stream flow to instantaneous flows using observed flows (cfs) for three watersheds and all watersheds combined.

From Q_d^o to Q_i^o	r^2	Watershed	From Q_d^v to Q_d^o	r^2
Q_i^o =1.52Q_d^o	0.79	Cascade River	Q_d^o =1.57Q_d^v	0.15
Q_i^o =1.52Q_d^o	0.82	Thunder Creek	Q_d^o =1.57Q_d^v	0.04
Q_i^o =1.21Q_d^o	0.63	Stehekin River	Q_d^o =1.34Q_d^v	0.45
Q_i^o =1.31Q_d^o	0.77	All Watersheds	Q_d^o =1.39Q_d^v	0.63
Q_i^o =1.52Q_d^o	0.79	Cascade River	Q_d^o =1.57Q_d^v	0.15

Q_d^o observed daily streamflow, Q_i^o observed instantaneous streamflow, Q_d^v VIC simulated daily streamflow

Despite the relatively strong linear relationship between *observed* daily and instantaneous flows (i.e., r^2 [coefficient of determination] values ranging from 0.63 to 0.82; Table 3), the relationship between observed daily flows and *VIC* simulated daily flows was relatively weak, especially as the watershed declined in size (i.e., r^2 values ranging from 0.04 to 0.63; Table 3). Therefore, an alternative approach was explored using relationships between the estimated peak flows (i.e., Q2 through Q100) among the observed daily and instantaneous streamflows, and observed daily and VIC simulated daily streamflows. A multiplier was calculated as the ratio of peak flows (e.g., Q25) determined for daily observations to VIC daily simulations multiplied by the ratio of peak flows for instantaneous observations and daily observations (Eq. 1).

$$Multiplier\ Q_n = \frac{Q_d^o}{Q_d^v} * \frac{Q_i^o}{Q_d^o} = \frac{Q_i^o}{Q_d^v} \qquad (1)$$

Where *Multiplier* Q_n is the multiplier for the peak flow with *n* return period and the right-hand side terms are as defined in Table 3 above. The multiplier essentially acts similar to unit conversion at the level of peak flow statistics, providing a transforming scalar for VIC simulated daily peak streamflow to estimated instantaneous-like peak streamflows. The multipliers developed for the three study watersheds increases with peak flow return period as well as watershed size (Fig. 10, Table 4). Estimates of higher peak flows, such as Q100, have more uncertainty relatively more frequent lesser peak flows (e.g., Q2) because there are fewer high flows events to generate statistical significance.

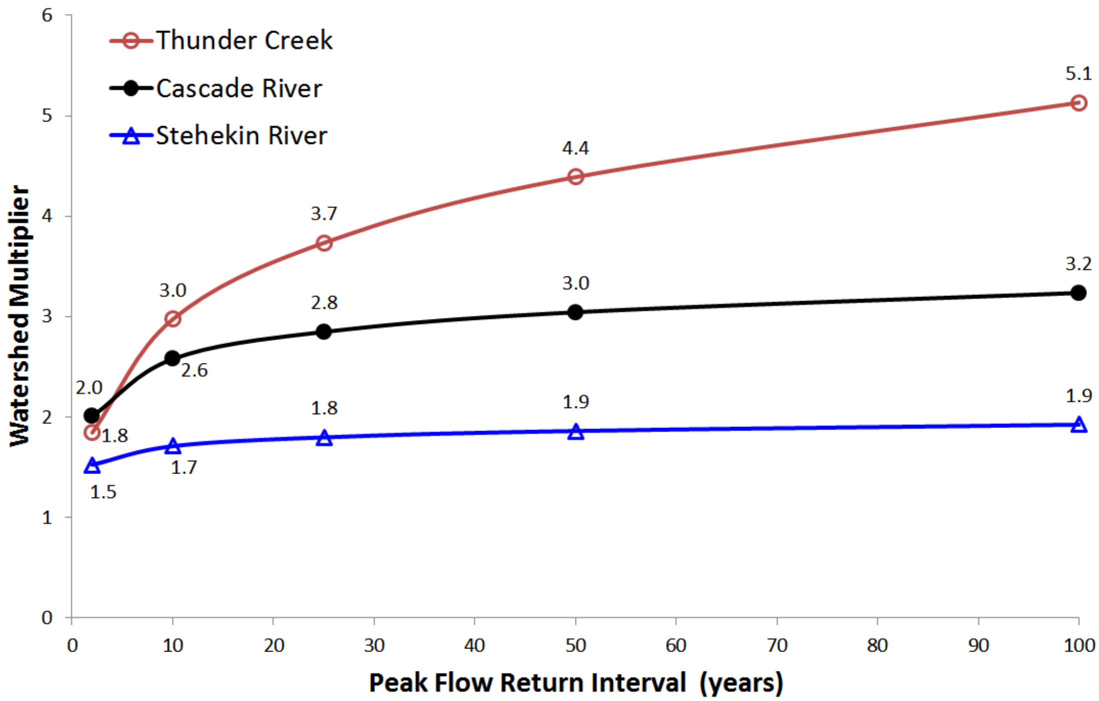


Figure 10. Multiplier developed from observational relationships for adjusting VIC simulated peak flows at Cascade River, Thunder Creek, and Stehekin River watersheds.

Table 4. Watershed multipliers used in transforming VIC simulated daily stream flow to instantaneous-like flows using observed streamflows (cfs).

Peak Flow Return Period (yrs)	Watershed Multiplier		
	Thunder Creek	Cascade River	Stehekin River
2	1.8	2.0	1.5
10	3.0	2.6	1.7
25	3.7	2.8	1.8
50	4.4	3.0	1.9
100	5.1	3.2	1.9

Using the multipliers in Table 4, gridded VIC simulated daily peak flows (i.e., return periods Q2, Q10, Q25, Q50, and Q100) were adjusted to represent VIC-based simulated instantaneous streamflows for historic and the 10-model GCM ensemble for 2040s and 2080s. Scaling the return periods of future VIC peak flows allows for the variability in the multiplier depending on the flow return period. Thus, use of these different multipliers preserves the distribution and non-linearity in the peak flows (i.e., a different multiplier is applied to different return periods). This approach assumes that the scaling between simulated and observed data remains the same in the future. We applied this approach on the three study watersheds where we had peak streamflows based on routed VIC modeled flows. Where watershed boundaries covered only a portion of a VIC grid cell, the fractional area within the watershed was calculated in ArcGIS and multiplied by the VIC streamflow magnitude. Thus, the edge of the watershed has relatively lower peak flow estimates than the central grid cells, which is foreseeable given the smaller drainage area (Fig. 11). As an example of results from this approach, the central and lower portions of the Cascade River and Thunder Creek watersheds have the largest projected Q100 in 2040s, more than 6000 cfs (Fig. 11), based on peak flow estimates from routed VIC daily streamflow simulations for 2040s amplified by the 3 to 5 times multipliers in Table 4 developed by observational streamflow relationships. The flow adjustment reflects the higher peak flows for instantaneous-like streamflow compared to original modeled average *daily* streamflow, plus peak flow changes driven by temperature and precipitation changes modeled in GCMs. Since the multipliers vary by watershed, additional streamflow measurements at smaller scales would need to be performed to test the scalability of this method.

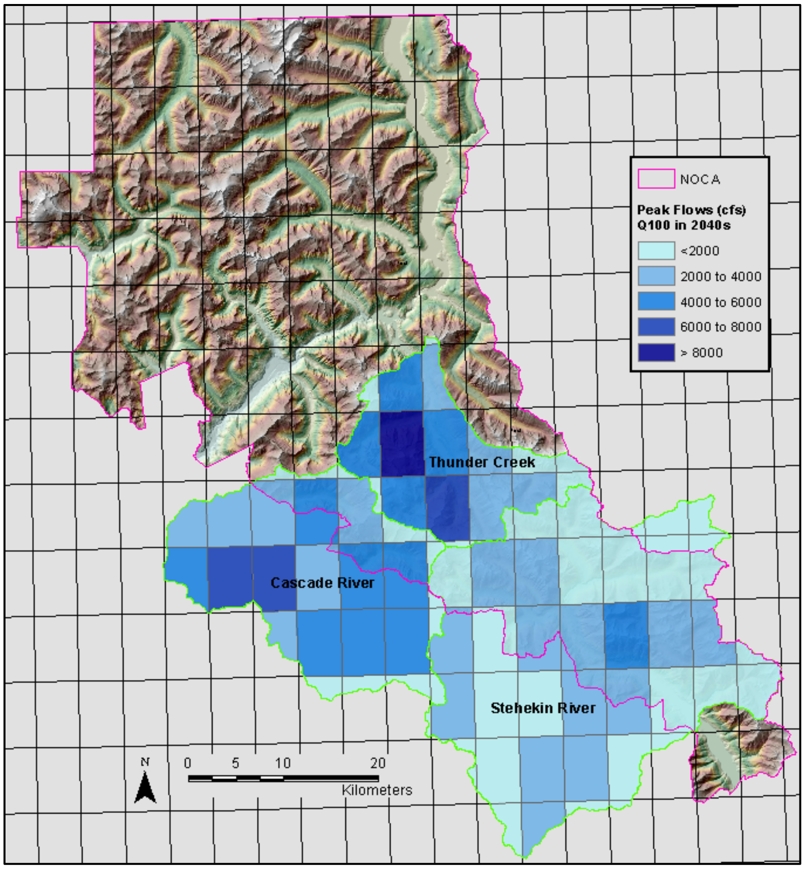


Figure 11. Peak streamflow with 100-year return period (Q100) estimated in the 2040s by adjusting VIC peak streamflow by a multiplier derived from observational data at three watersheds in NOCA. The grid is 1/16th degree resolution of the VIC model simulation.

Amending Streamflow with StreamStats

Another approach to adjusting peak streamflow estimates based on model simulations of future streamflow uses methods developed for Olympic National Park (Tohver et al. 2012). This approach was found to capitalize on the strengths of the VIC model in capturing the projected responses of watersheds to climate change and of the USGS StreamStats tool, which more realistically determines the absolute magnitude of peak flows. StreamStats was developed by USGS in cooperation with ESRI, Inc. as a web-based Geographic Information System application for water resource management and engineering design, such as culverts (http://water.usgs.gov/osw/streamstats/index.html). The program provides streamflow statistics for ungaged streams based on regression equations created from instantaneous streamflow observations for states such as Washington (USGS 2001; Sumioka et al, 1998). These regression equations estimate streamflow based on the contributing drainage area (A) in square miles and mean annual precipitation (P) in inches. Estimated streamflow statistics from StreamStats include Q100 and mean annual flow (Q2) in cubic feet per second. Regression equations developed for the region of Washington that includes the three focus watersheds within NOCA are listed in Table 5. The two hydrologic regions within NOCA are separated by the crest of the Cascade Mountains into a westside (region 2) and eastside (region 4). StreamStats recently underwent a revision update and new regression equations have been developed for different Hydrologic Regions (Mastin et al. 2016). The online use of StreamStats version 4 (https://water.usgs.gov/osw/streamstats/) with updated equations for Washington is now available online as of autumn 2018. The new flood frequency analysis defines different hydrologic regions and the new regression equations for eastern Washington watersheds include forest cover as an additional predictive variable (Mastin et al. 2016).

Table 5. Flood peak streamflow regression equations for watersheds assessed within NOCA.

Watershed	Hydrologic Region	Streamflow (Q) Return Period (Years)	Regression Equation*
Cascade River and Thunder Creek	2	Q2	$0.090A^{0.877}P^{1.51}$
	2	Q10	$0.129A^{0.868}P^{1.57}$
	2	Q25	$0.148A^{0.864}P^{1.59}$
	2	Q50	$0.161A^{0.862}P^{1.61}$
	2	Q100	$0.174A^{0.861}P^{1.62}$
Stehekin River	4	Q2	$0.025A^{0.880}P^{1.70}$
	4	Q10	$0.179A^{0.856}P^{1.37}$
	4	Q25	$0.341A^{0.850}P^{1.26}$
	4	Q50	$0.505A^{0.845}P^{1.20}$
	4	Q100	$0.703A^{0.842}P^{1.15}$

*A = contributing area [mi^2]; P = mean annual precipitation [in]; Source: USGS (2001) Fact Sheet 016-01; Note that these equations have been updated since this analysis was completed (Mastin et al. 2016).

One approach uses the future precipitation from the VIC simulations in the StreamStats equations for peak flows, thereby adjusting the estimated peak flows with future precipitation projections. A second approach multiplies the peak flows provided by StreamStats by the ratio of future to historic streamflow simulated by VIC (i.e., adjust the flow estimates by the projected *relative* change in future flows) as in Tohver et al. (2012).

The regionally specific equations were applied at each grid cell using the grid cell area (~12.4 mi^2) and the annual precipitation [in] employed as forcing data for the VIC model simulations used for the historical simulation and the ensemble of the ten GCMs for two different time periods (2040s and 2080s). Thus, each grid cell has estimated StreamStats peak streamflow with five different return periods for historical conditions and future modeled conditions based on an ensemble at two different future time periods. Thirty of the 280 grid cells lie on the crest; therefore, flows were calculated for each portion of the grid cell based on the proportional area of the cell within each region calculated by the ArcGIS Spatial Analyst Tabulate Intersection tool. The tool returned the proportional area and percentage of area of each grid cell within the two regions. These data were tabulated and summed using Excel pivot tables to eliminate duplicate identifiers and then rejoined to the fishnet (grid) centroids to convert to two separate rasters (i.e., gridded data): an east and a west raster. The bisected grid cells were the only common cells in the two datasets. The east and west rasters were mosaicked together and set to overlap and average the values of the bisected grid cells.

The same suite of peak streamflows was also created at each grid cell by multiplying the StreamStats peak flows, derived from the historic VIC simulated mean annual precipitation mentioned above, by a VIC future peak flow ratio calculated as the ratio of future peak flow to historic peak flow. This approach encapsulates more of the hydrologic processes captured in the VIC hydrologic model than StreamStats equations with projected future precipitation alone.

Comparison of Methods and Results

Our initial comparison of the different method of estimating peak streamflows explored streamflows estimates for the three study watersheds: Thunder Creek, Cascade River, and Stehekin River. At the watershed scale, estimated flows can be compared to streamflow records, such as instantaneous streamflow measured by USGS. The peak streamflow estimates from these records are less than the estimates based on StreamStats for all return periods for Thunder and Cascade watersheds, but more for Stehekin watershed (Fig. 12). These results suggest that the mean annual precipitation or the regression equation parameters may be biased (i.e., contain errors) in the StreamStats tool. These biases may be related to the high elevation location of these watersheds within the hydrologic region used to develop the regression. Note that these equations were recently adjusted, particularly in eastern Washington (Mastin et al. 2016). To explore the effect of altering the mean annual precipitation in the StreamStats equations, we estimated watershed average mean annual precipitation used for the VIC modeling by averaging the mean annual precipitation of all the grid cells within or intersecting each watershed. These VIC-derived mean annual precipitations were 18 to 32 percent less than mean annual precipitation from the StreamStats tool. Consequently, the estimated peak flows calculated by the StreamStats equations using the VIC-derived precipitation were less for all return periods than estimates by the StreamStats tool (Fig. 12). Peak flows estimated from StreamStats with VIC precipitation were generally lower than those derived from USGS instantaneous records at Thunder and Stehekin watersheds, but higher for Cascade watershed. The peak flow estimates from the VIC simulated peak flows adjusted by a multiplier derived from observations calculates peak flows equal to the USGS instantaneous flows because of the derivation of the multiplier (Eq. 1; Fig. 12); thus, this approach matches the observed instantaneous peak flow estimates the closest among the methods for all return periods.

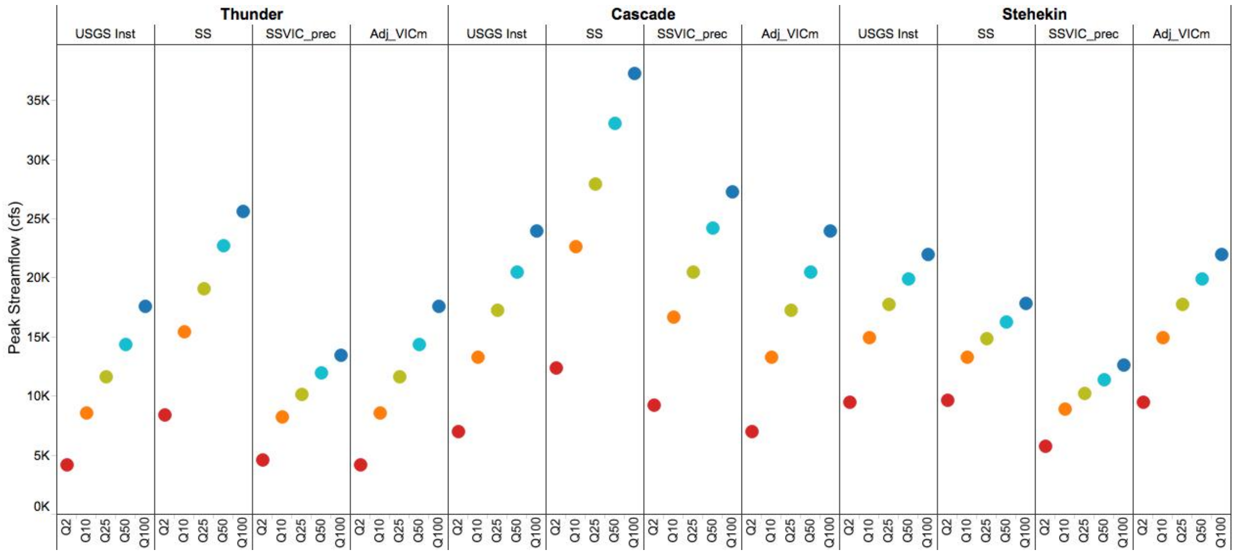


Figure 12. Estimated peak streamflows with return periods of 2 to 100 years (i.e. Q2, Q10, Q25, Q50, and Q100) estimated from instantaneous streamflow USGS gage data (USGS Inst), StreamStats tool (SS), StreamStats equations with VIC model precipitation (SSVIC_prec), and VIC simulated streamflow adjusted by the multiplier derived from observational relationships (Adj_VICm) for three watersheds in North Cascades National Park Complex.

Estimating Peak Streamflow at Small Scales

In order to be able to compare the different methods used to estimate peak flows at scales smaller than a watershed, all approaches were converted to units of cubic feet per second (cfs), units commonly used by land managers, and presented at a scale of the grid cell (~34 km^2). The methods were numbered and abbreviated as described in Table 6. A data cube provides a representation of the suite of data generated for each grid cell using these various methods (Fig. 13). We compared the different methods using ArcGIS and Excel against a baseline (called Method 1) we considered to be the peak flows estimated with StreamStats applied with historical precipitation from VIC, essentially representing historical peak flow magnitudes based on instantaneous flows. Peak flow estimates based on USGS gage data are not available at smaller scales, such as a grid cell, and thus, cannot be used as baseline for this comparison.

Table 6. Method, abbreviation, and description of methods used to estimate peak streamflow.

Method Number	Method Abbreviation	Method Description
Method 1	SSVIC_HistP	StreamStats equations using VIC historical precipitation (*Baseline*)
Method 2	VIC_Hist	VIC historical simulated streamflow
	VIC_2040	VIC 2040s simulated streamflow
	VIC_2080	VIC 2080s simulated streamflow
Method 3	SSVIC_2040P	StreamStats equations using VIC 2040s precipitation
	SSVIC_2080P	StreamStats equations using VIC 2080s precipitation

Table 6 (continued). Method, abbreviation, and description of methods used to estimate peak streamflow.

Method Number	Method Abbreviation	Method Description
Method 4	SSVIC_2040R	StreamStats equations multiplied by the ratio of VIC 2040s to historical simulated streamflow
	SSVIC_2080R	StreamStats equations multiplied by the ratio of VIC 2080s to historical simulated streamflow
Method 5	VIC_HistObs	VIC historical simulated streamflow adjusted by a multiplier developed based observed instantaneous streamflow
	VIC_2040Obs	VIC 2040s simulated streamflow adjusted by a multiplier developed based observed streamflow
	VIC_2080Obs	VIC 2080s simulated streamflow adjusted by a multiplier developed based observed streamflow

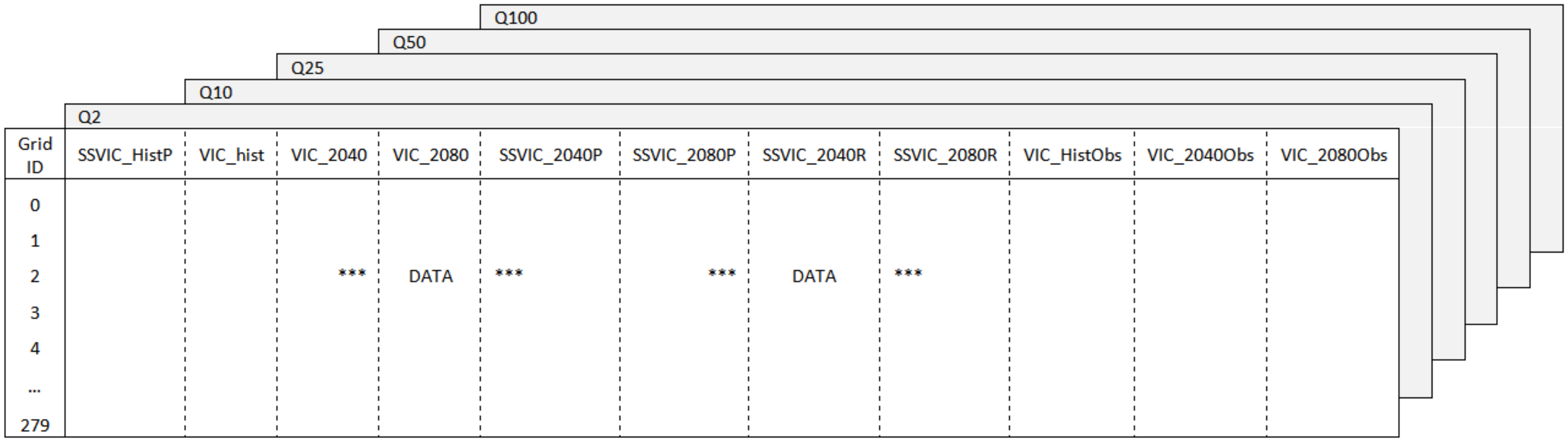


Figure 13. Data cube of peak flow estimate from various methods generated for each of 280 grid cells located in and around NOCA. The description of the method abbreviation is provided in Table 5. The grid ID aligns with the grid cell's latitude and longitude described in Appendix C.

As a preliminary analysis of the differences between various estimates of future peak flows, we examined the results at one grid cell (#87), centrally located in Cascade River watershed (see Appendix C, Fig. C4). This central location minimizes the influence of the watershed edge proportional flows estimated by the VIC simulated streamflows adjusted by the multiplier developed based on observed streamflow (Method 5). At this cell location, VIC simulation of historic flows and both future flows (Method 2) predicts lower (24 to 62 %) flows than StreamStats with VIC historical precipitation (Method 1) (Fig. 14, Table 7), which likely reflects the daily scale of VIC and the instantaneous scale of StreamStats equations (note the points lie below the 1:1 line in Fig. 14). Therefore, the flows from StreamStats may generally provide higher peak flows for designing and planning than future stream flows estimated by VIC *daily* data.

In general, peak flows with VIC adjustments (Methods 3, 4, and 5) project higher flows than StreamStats with VIC historic precipitation alone, especially at higher return periods (Fig. 14; Table 7). These methods are similar at lower peak flows (Q2), but depart from each other at higher flows (Q100). This indicates these methodologies project expanded differences in higher peak flows compared to historical peak flows further into the future. VIC peak flows adjusted by the observations multiplier (Method 5) estimated the highest peak flows at return periods above Q2 (Fig. 14). The percent change from the baseline at different future peak flows is relatively consistent (±1 to 10%) among the different peak flow return periods for StreamStats adjusted methods (Methods 3 and 4; Table 7). However, the percent change in peak flow estimates increases remarkably (5 to 90%) as the return period increases (i.e., larger flows) for the method that adjust VIC simulated peak flows by the observation multiplier (Method 5).

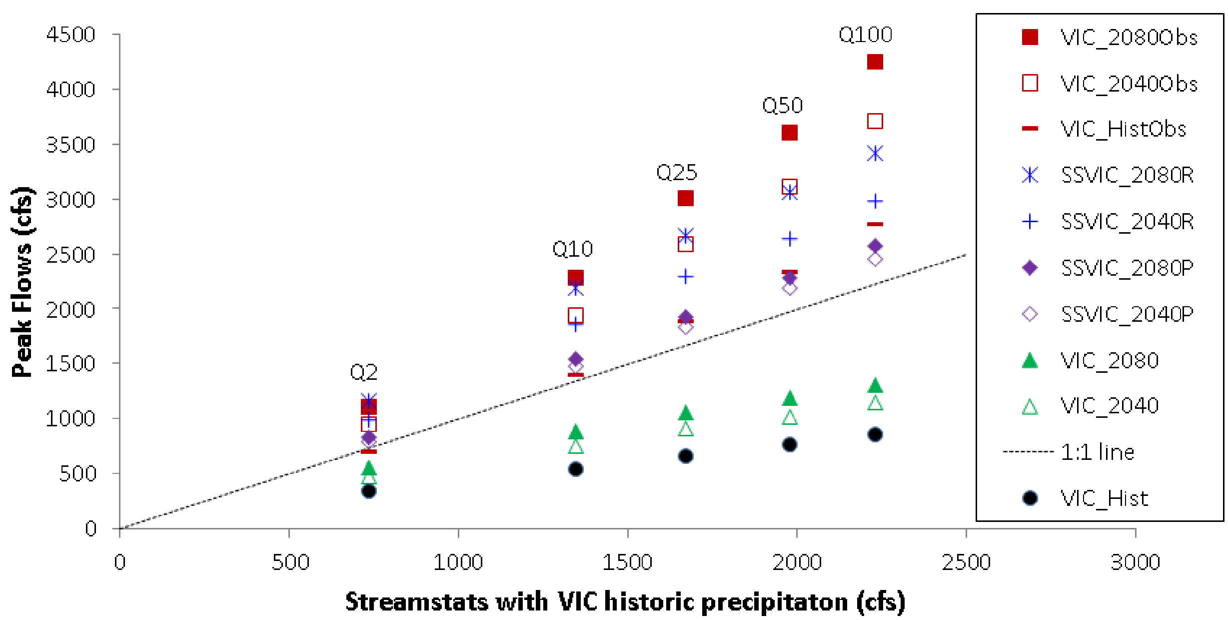


Figure 14. Peak streamflows estimated by various methods compared to a baseline estimated by StreamStats equations using VIC historical precipitation for *one* grid cell, #87, located at latitude 48.46875, longitude -121.21875 in Cascade River watershed. Code descriptions detailed in Table 6.

Table 7. Peak streamflows estimated by various methods and percent change from a baseline estimated by StreamStats equations using historical precipitation at *one* grid cell, #87, located at latitude 48.46875, longitude -121.21875 in Cascade River watershed. Method descriptions detailed in Table 6, except that "F" indicates both 2040s and 2080s, and "ratio" replaces R.

	Method 1 SSVIC_HistP	Method 2 VIC		Method 3 SSVIC_FP		Method 4 SSVIC_Fratio		Method 5 VIC_Obs	
Peak Flow	Baseline Flow (cfs)	Flow (cfs)	Pct. Change	Flow (cfs)	Pct. Change	Flow (cfs)	Pct. Change	Flow (cfs)	Pct. Change
Q2_hist	732 [a]	351	-52% [b]	NaN	NaN	NaN	NaN	705	-4% [b]
Q10_hist	1344 [a]	546	-59% [b]	NaN	NaN	NaN	NaN	1408	5% [c]
Q25_hist	1671 [a]	663	-60% [b]	NaN	NaN	NaN	NaN	1888	13% [c]
Q50_hist	1979 [a]	767	-61% [b]	NaN	NaN	NaN	NaN	2335	18% [c]
Q100_hist	2231 [a]	858	-62% [b]	NaN	NaN	NaN	NaN	2777	24% [c]
Q2_2040	NaN	475	-35% [b]	801	9% [c]	990	35% [c]	953	30% [c]
Q10_2040	NaN	755	-44% [b]	1475	10% [c]	1859	38% [c]	1947	45% [c]
Q25_2040	NaN	910	-46% [b]	1836	10% [c]	2294	37% [c]	2591	55% [c]
Q50_2040	NaN	1024	-48% [b]	2192	11% [c]	2643	34% [c]	3118	58% [c]
Q100_2040	NaN	1145	-49% [b]	2456	10% [c]	2978	33% [c]	3706	66% [c]
Q2_2080	NaN	556	-24% [b]	837	14% [c]	1160	58% [c]	1117	53% [c]
Q10_2080	NaN	888	-34% [b]	1545	15% [c]	2186	63% [c]	2289	70% [c]
Q25_2080	NaN	1058	-37% [b]	1924	15% [c]	2667	60% [c]	3013	80% [c]
Q50_2080	NaN	1184	-40% [b]	2282	15% [c]	3056	54% [c]	3605	82% [c]
Q100_2080	NaN	1313	-41% [b]	2576	15% [c]	3414	53% [c]	4249	90% [c]

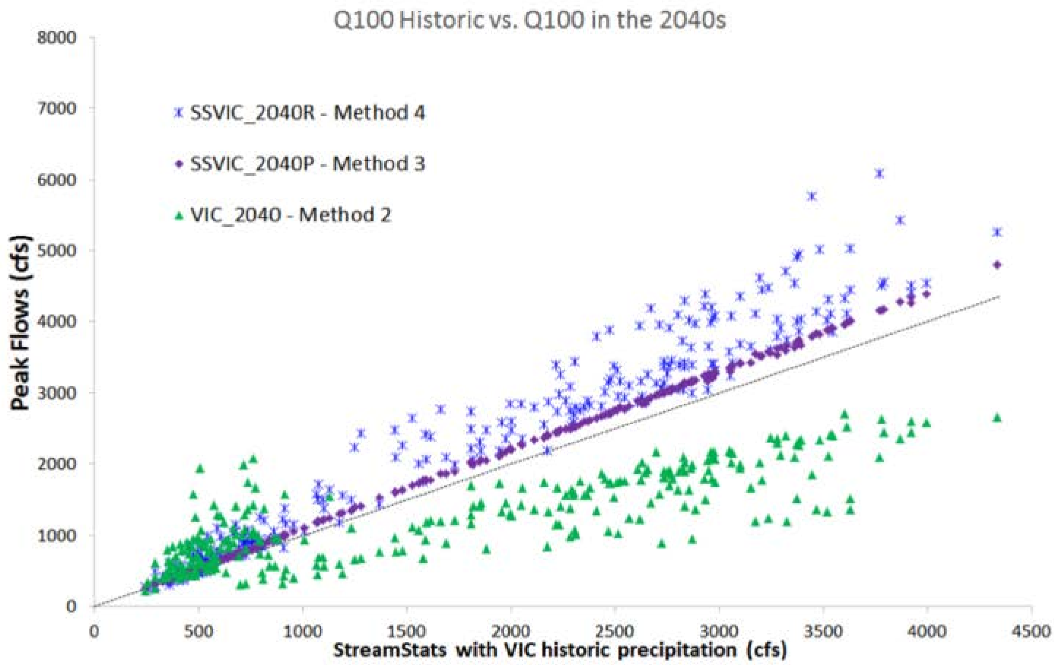
[a] Baseline estimated by StreamStats equations using historical precipitation (also shaded in gray)

[b] Indicates *declining* future flows (also shaded in yellow)

[c] Indicates *increasing* future flows (also shaded in blue)

Analysis of the results for one grid cell may not reflect the general patterns of all the grid cells encompassing the park. Therefore, we assessed the entire dataset to detect spatial patterns and differences between the various methods and in future time periods. We analyzed the entire gridded region encompassing NOCA to understand differences between Method 2, 3, and 4 compared to the *baseline* peak flows from StreamStats with VIC historic precipitation. Method 5 could not be compared because it did not cover grid cells outside the three study watersheds. Similar to the single cell analysis, VIC model estimates of future Q100 (Method 2) predicts lower peak flows than the baseline, except at lower flows (Fig.15a). This suggests that VIC estimated peak flows may be above or below the baseline peak flows in grid cells with estimated Q100 less than 1,300 cfs (i.e., smaller streams). These are predominantly east of the Cascade crest or the leeward side of individual mountains west of the crest. Both Methods 3 and 4 estimate peak flows in excess for the baseline for grid cells above 1,000 cfs and above, and similar to the baseline for grid cells below 1,000 cfs (Fig. 15a). However, Method 3 lacks variability compared to Method 4, reflecting the added hydrologic processes, such as snowmelt, captured by the VIC model that is missed in Method 3 based on future precipitation projections alone. These findings from comparing methodologies are similar for Q100 in both 2040s and 2080s; however, the differences between Methods 3 and 4 compared to the baseline are even greater, especially at higher flows in the 2080s (Fig., 15a, b). These patterns were similar for the lesser peak flows, Q2 through Q50.

(a) 2040s



(b) 2080s

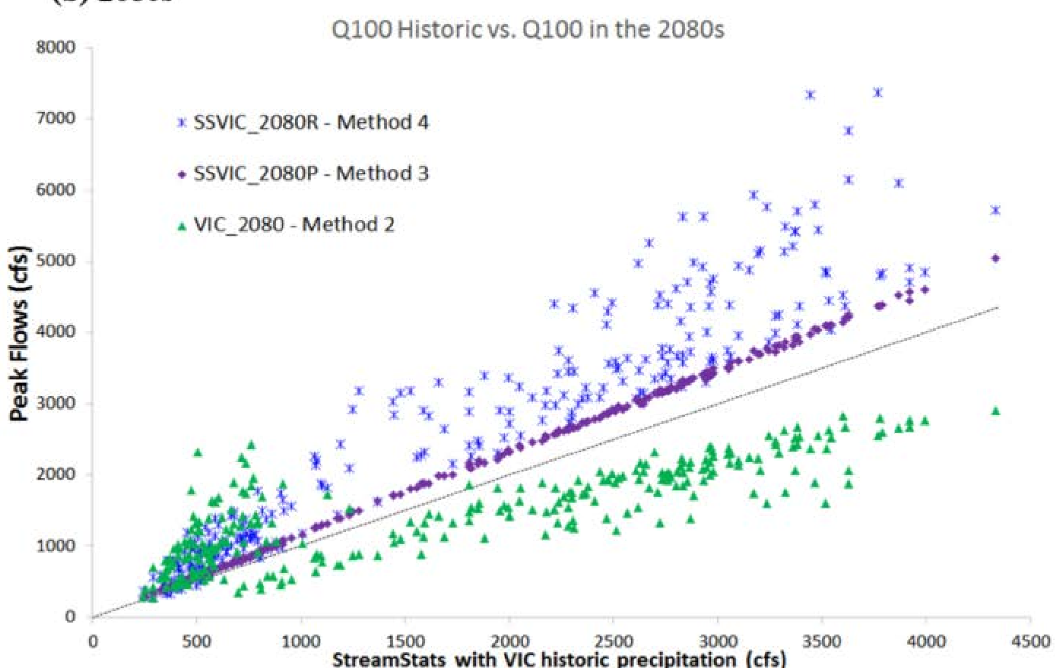


Figure 15. Q100 estimated by various methods compared to a baseline Q100 estimated by StreamStats equations using VIC historical precipitation for all grid cells in NOCA for the (a) 2040s and (b) 2080s. Method codes and descriptions described in Table 6.

We examined the visual differences in peak streamflows in the future compared to the past by calculating the ratio of future projected peak streamflow to historic peak streamflow as modeled by VIC. As an example, the ratios for Q100 in 2040s and 2080s are shown in Figure 16a. All of NOCA is projected to see increases in 100-year flows in the future with greater increases over time. However, the ratios of Q2 show a few locations with decreasing mean annual flows (Q2) within NOCA and less increase on the eastern side of the park than projected for Q100 (Fig. 16b). Therefore, the projected changes in peak flows in a particular location may not be the same for different peak flow return periods, which is also evident when examining individual cells using the Excel tools discussed below in *Excel Tools for Peak Streamflow*s.

Several more advanced geospatial analyses can be undertaken to compare the different methodologies for estimating peak flows and their spatial-temporal patterns, but are beyond the scope of this study. For example, future analysis could employ the Empirical Bayesian Kriging tool in ArcGIS Geostatistical Analyst to explore patterns through better accounting of the variation in climate data and enhanced displays of change patterns. Additionally, the ArcGIS Spatial Statistics tool could be used to perform Getis-Ord GI* Statistic Hot-Spot Analysis, which would measure the significance of clustering of changes between historical and future peak streamflow (i.e., identify clustered areas with extreme low or high change). Also, the VIC hydrologic model is a macro-scale model that provides hydrologic data on a $1/16^{th}$ degree grid cell or larger. Finer scale hydrologic data could be acquired from a higher resolution hydrology model, such as Distributed Hydrology Soil Vegetation Model (DHSVM), which may be more proficient at capturing local scale hydrology for culverts. These analyses may be the subject of future research.

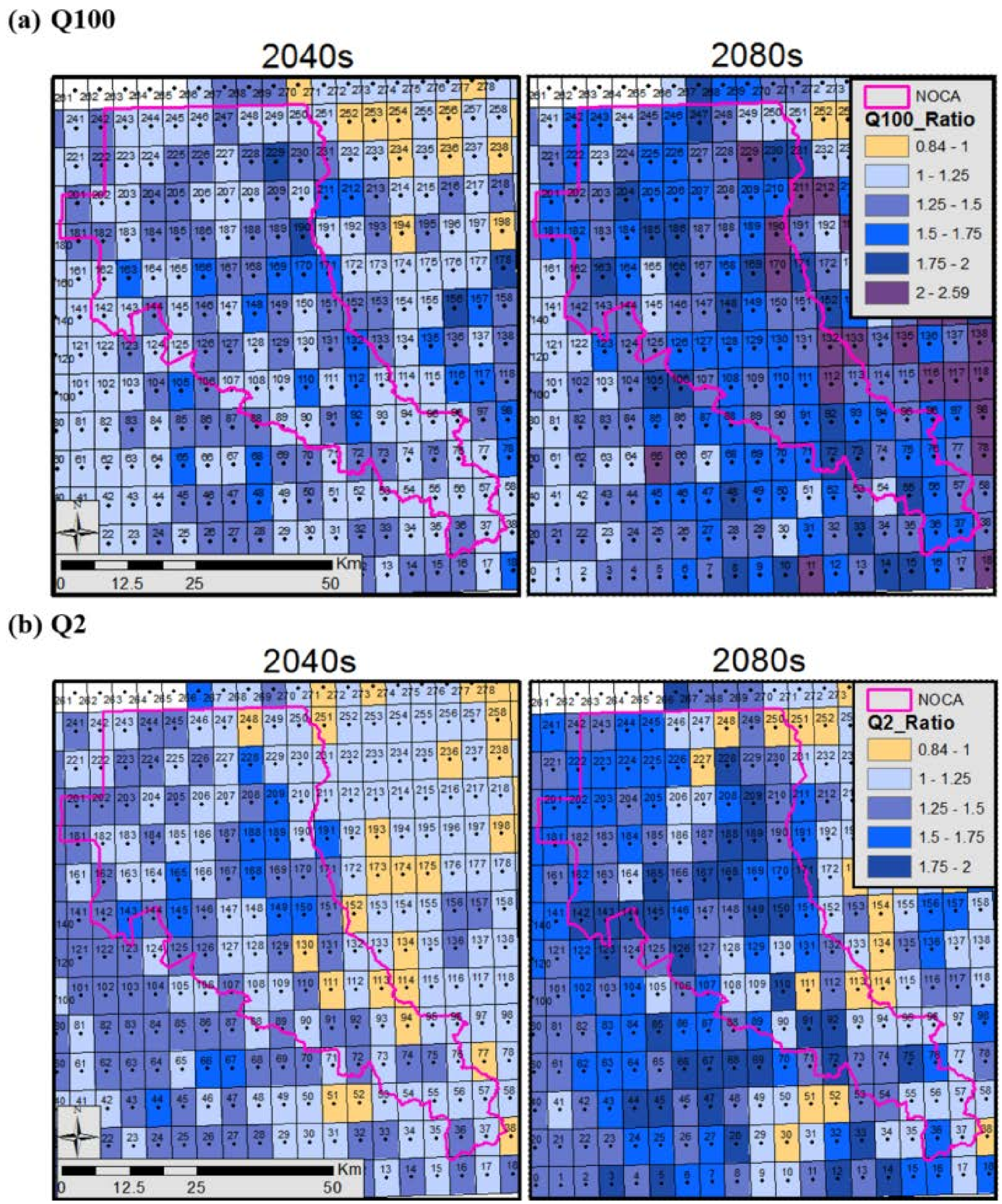


Figure 16. Shifting trend in the ratio of (a) Q100 and (b) Q2 in 2040s (left side) and 2080s (right side) to historical (1916–2006) corresponding peak stream levels. Ratios >1 indicate increasing peak flows in the future (blue). Ratios <1 indicate decreasing peak flows (beige).

Excel Tools for Peak Streamflows

Simple tools were designed in Excel based on the VIC future streamflow projections and employed in a study in Olympic National Park by Tohver et al. (2012). Three versions were created. One provides the future VIC projections in mm/day and another is in units of cfs. A third version provides the ratios of future to historic streamflows as projected by VIC. Each of these tools provides peak flow information for individual grid cells based on a map key with unique grid cell ID numbers associated with the centroid latitude and longitude of each grid cell (see Appendix C; Fig. C4). The Excel spreadsheets contain a main tab that provides plots of the flood statistics for a grid cell, while the other tabs contain the data referenced by the first tab. For each of these tools, the user can enter in a grid cell ID number on the first tab that corresponds to the grid cell of interest (e.g., where a culvert is located). The data and figures are automatically updated to reflect the flood statistics for that particular grid cell. Uncertainty in estimated future peak flows is provide in the tool within the table and figures showing peak flow information for 10 different future climate scenarios for the 2040s and 2080s. An example of the ratio Excel tool is provided in Figure 17. Demonstration of how to use these tools to estimate flows for a culvert is provide in Appendix C.

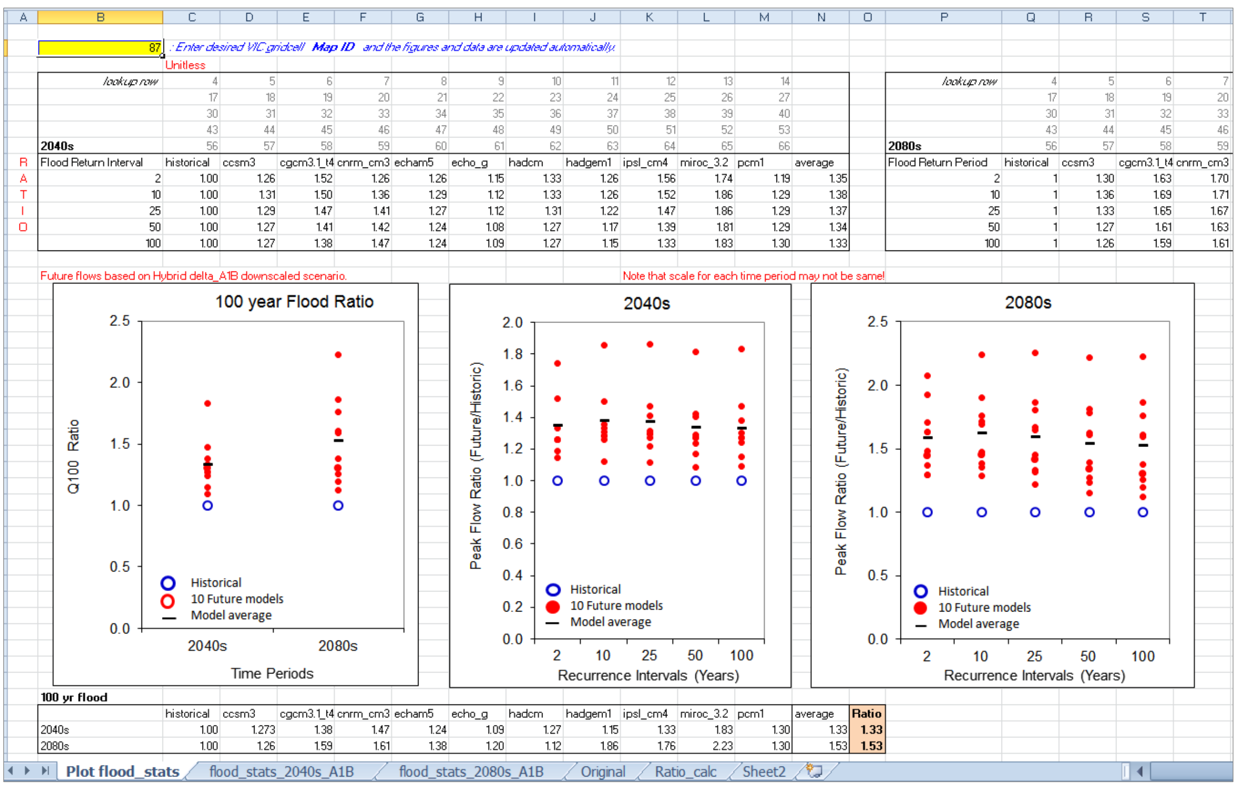


Figure 17. Excel tool of ratios of future to historic streamflow projected by VIC. User inputs the grid cell ID number located from a map in the yellow box. Data and figures are updated automatically.

Evaluation of Existing Culvert Inventory and Recommendations for a Geospatial Database

One objective of this project was to better understand the information and conditions of culverts stored in the asset inventory of NOCA. The existing asset inventory of culverts is retained in a database called Facility Management Software System (FMSS), accessible to NPS personnel. This inventory contains limited information (e.g., culvert material, length, width, location description), but is not georeferenced to a geodatabase such as ArcGIS. Road culvert locations are referenced to mile post and trail culvert locations are measured in feet using a calibrated wheel, but this cannot be accurately converted into GIS due to the bumpy trail terrain and mountainous terrain.

We conducted field reconnaissance of road and trail culverts in the summer of 2013 to evaluate the completeness of the existing asset inventory and generate a planning level estimate of time needs for a new trail survey. First, we inventoried culverts along a 5.3-mile section of the Cascade River Road. FMSS documents 55 galvanized steel culverts along this section or approximately 10 culverts every mile; many culverts (55%) are the same diameter (i.e., 24 inches). To aid our field surveys, we approximately located the culverts in a GIS database using the milepost information, aerial photographs, and stream locations (Fig. 18) However, definitively locating the culverts documented in the FMSS inventory in the field was still challenging, except for the large ones that were located based on the larger diameter dimensions (e.g., much larger than adjacent culverts).

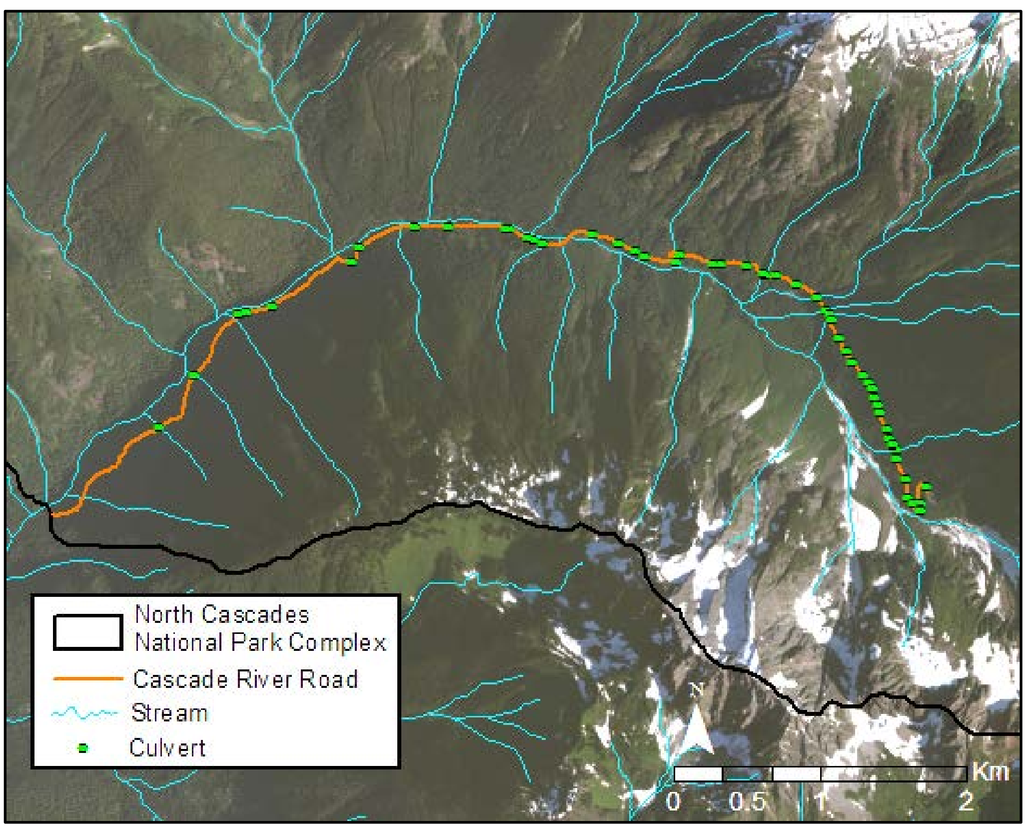


Figure 18. Culverts within FMSS inventory located along Cascade River Road.

Based on this mapping, the density of culverts is variable - higher at the higher elevations, where less flow converges. A georeferenced field inventory (e.g., with a GPS unit) would reveal if any culverts were missing from the FMSS database and provide more accurate location information for analyses and future detection. Using GIS to identify where culverts might exist along a road can suggest where culverts possibly exist, but will likely underestimate the number of culverts. For example, the number of intersections between the Cascade River Road and streams in Washington State Department of Natural Resources geodatabase (DNR HYDRO) within NOCA boundaries would suggest 12 culverts rather than the 55 currently within the FMSS database, roughly 22% of the currently known culverts.

A trail inventory was conducted to understand the time necessary to inventory trail culverts, their frequency, and ease of data collection. The field reconnaissance of the East Bank Trail is captured in Appendix A. This trail was selected because of its relatively quick access and lack of culvert information. The reconnaissance took about 4 hours (excluding ½ hour lunch) and covered 3.8 miles. A total of 11 culverts were identified, but two of these were non-functioning crossings (culverts were removed and placed by the side of the trail). Culverts were made of both corrugated and smooth metal, except for two plastic ones at the beginning of the trail. The smooth metal culverts appear to be the original steel riveted culverts that may have been installed during the time when gold was mined in this area. The majority of culverts convey streams, but many are ephemeral (i.e., seasonal) and had little or no flow in August. All the culverts encountered were along the East Bank Trail prior to it splitting north to Hidden Hand Pass. This is not surprising because the East Bank Trail crosses along a hillslope face, which drains down to Ruby Arm of Ross Lake; whereas, the trail splitting north begins a gentle rise to a drier ecosystem. Eighteen locations were natural stream drainages without culverts, where flow passed over the trail, often through large rocks and cobbles. These appeared to be remarkably stable, with little erosion evident at the time of the survey. Some of the existing culverts need maintenance due to plugging, crushing, or a perched outlet that is eroding downstream material. This field reconnaissance gives an indication of time and expected outcomes when surveying a similar trail and collecting only basic information.

Data on culverts are often missing or incomplete from agency asset inventories, as evident above; however, even incomplete data provides vital information for managing and analyzing transportation networks. To highlight the data needs associated with the disruption of transportation at culverts from climate change, graduate students and a research associate at the University of Washington developed a culvert inventory mobile app. This app facilitates collection of basic information, including photographs, about culverts by tailoring a geodatabase accessible from ESRI's Collector App (Fig. 19). They entered the mobile app in the ESRI Climate Resilience App Challenge 2014 and were one of the top 13 apps submitted in the international competition (http://www.esri.com/software/landing_pages/climate-app). The app[1] was designed to provide

[1] In 2016, NOCA sponsored a National Park Service George Melendez Wright Young Leader in Climate Change Intern, Angelina Nguyen to review the app and work with NOCA staff to integrate this research

managers of road and trail networks the ability to use citizen scientists to collect basic information about culverts (video at https://vimeo.com/97151747).

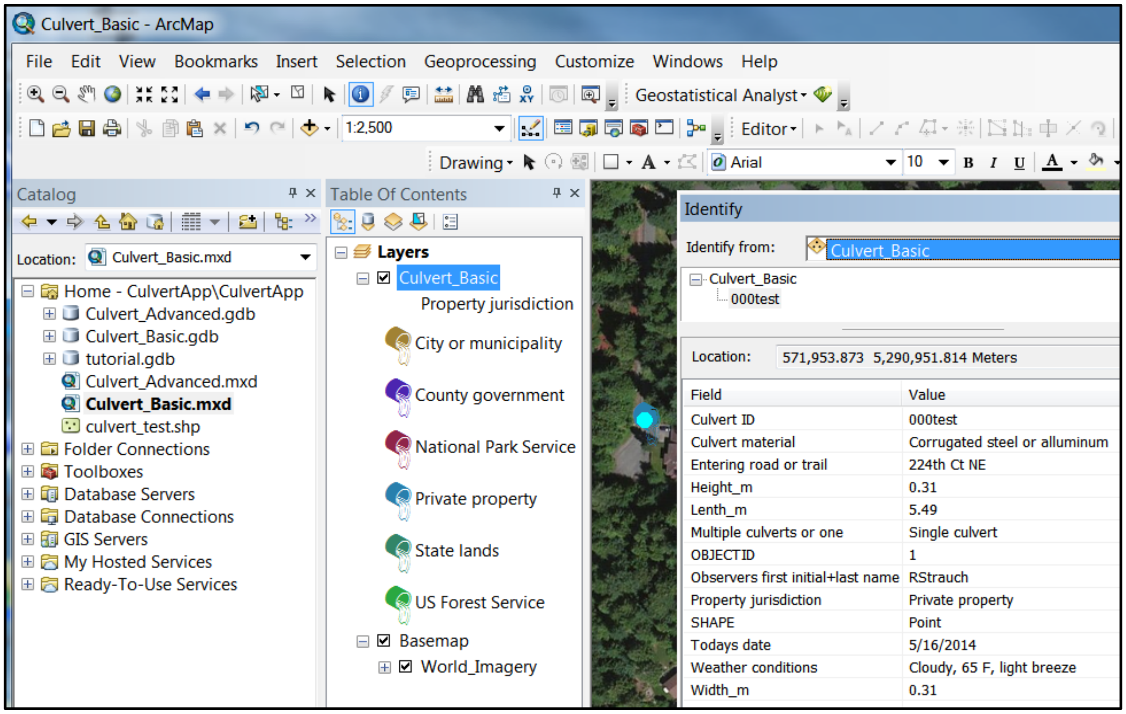


Figure 19. Geodatabase created for collecting basic information about culverts.

A more advanced version of the geodatabase (*Culvert_Advanced.gdb*) was also developed based on an extensive draft data sheet developed collaboratively with NPS scientists (see Appendix B). This culvert inventory data sheet could be used to gather comprehensive information about culverts by trained personnel, which could be used in maintenance, monitoring, design, and/or construction of culverts. The geodatabase is designed for use in ArcGIS so that collected data could be geospatially analyzed and related to climate information such as the peak flows developed in Estimating Peak Flows Under Future Climate discussed above. The basic and advance geodatabase can be used by agencies managing culverts to expand their existing inventories and use the information for assessments, operations, monitoring, and planning activities, including transportation network vulnerability to shifting hydrology.

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with NOCA operations and management. Angelina completed three reports that are listed in the references and available through from the NPS.

Conclusion and Recommendations

The integrity of culvert systems is a key component affecting the longevity of the transportation infrastructure within NOCA. Adapting culvert management strategies to changing hydrologic regimes requires site-specific knowledge of projected changes in hydrologic flow, adaptive capacity of local culverts (i.e., design, location, condition), local landforms, and institutional memory of past extreme events and management responses. We found that information on culverts in the FMSS database is insufficient to support managers in adapting culvert management to changing climates. Culvert inventories are incomplete, culvert locations are not georeferenced (i.e., only noted by wheel mile), and conditions and dimensions are rarely updated. Georeferenced culverts would allow review of culverts (and current capacity and condition) in the context of projected hydrologic flows, landforms, aquatic organism passage, and visitor use estimates. We developed a more detailed data sheet, geospatial database, and mobile app to facilitate culvert mapping and comprehensive data collection by park employees or citizen scientists. To advance the understanding of climate change impacts, this study focused on estimation of peak flows often used to assess and design culverts. In particular, we provided various methods to estimate future peak flows under a changing climate and simple tools to incorporate future streamflow estimates into infrastructure management.

Estimates of current peak streamflow using the USGS StreamStats tool for ungaged streams are greater than the VIC hydrological model estimates based on daily streamflow, and thus, this tool is appropriate for estimating the magnitude of current peak streamflow based on instantaneous flow. However, in the future, the additional hydrologic processes captured by the VIC model lead to higher peak flow estimates than those estimated by the StreamStats regression equations even with integrating future precipitation. A straightforward way to incorporate the VIC modeled future projections in streamflow into the conventional StreamStats tool for estimating the magnitude of peak streamflows, at any culvert location, is to multiply the StreamStats estimated peak flows by the ratio of VIC future to historic peak streamflow. These ratios can be easily acquired from the Excel spreadsheet tool which provides these ratios for different peak flow return periods as well as different future GCMs realizations, disclosing model uncertainty. Appendix C provides a step-by-step process to apply this approach to an existing culvert.

The mean annual flow (Q2) estimated with the process described in this study could be used in the culvert design approach based on bankfull width recently developed for Washington State (Wilhere et al. 2017). In addition to streamflow information, other information can be used to assess hazards at road-stream crossings, such as upstream sediment and channel stability, acquired from resources such as landform maps and disturbance data collected by the NPS North Coast and Cascades Network (NCCN) landscape dynamics monitoring program. Although this report focused on peak streamflow impacts on culverts, there are additional climate impact pathways that affect culvert integrity (e.g., increase sediment transport into streams from reduced snowpack and retreating glaciers). These pathways should also be considered in managing transportation systems in mountainous environments as climate changes. It is also worth noting that culverts can be impacted by intense summer thunderstorms that are not resolved directly by GCMs and thus not in VIC model simulations, although some progress has recently been made ascertaining thunderstorms for GCMs (Singh et al. 2017).

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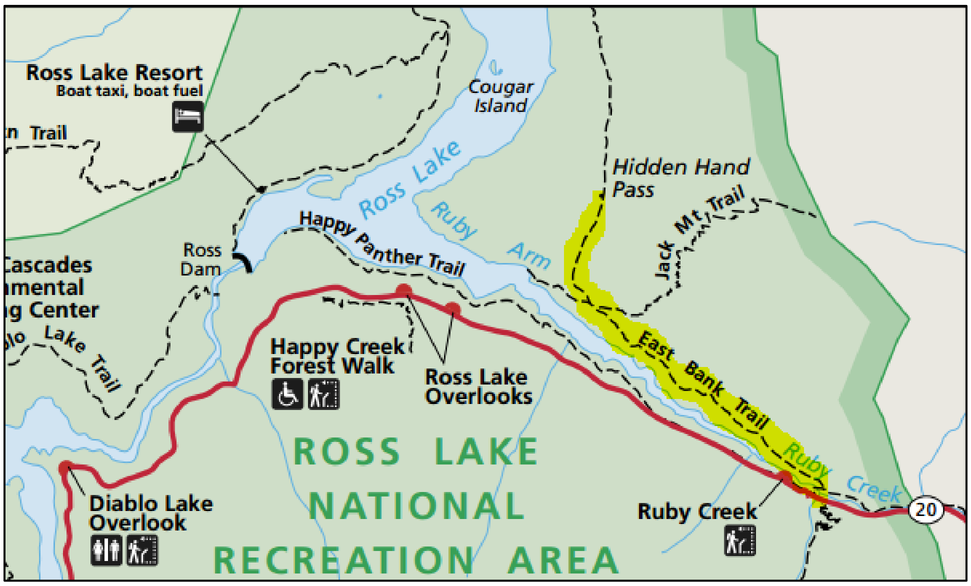
Appendix A. Culvert Inventory of East Bank Trail

East Bank Trail – North Cascades National Park Complex

Date: 8/8/13
Time: 9:00 AM – 1:30 PM
Weather: Clear, sunny, upper 70Fs
Crew: Ronda Strauch, Mackenzie Grow, and Chris Lauver
Location: Started at Hwy 20 and ended about 1 mile beyond trail intersection with Jack Mtn. Trail



Data Collection

Culvert #	Material	Diameter	Stream/Drainage	Comments
0	Corrugated Metal	13”	Drainage	Hwy 20 Bridge: stormwater down pipe
Bridge	–	–	Stream	Over Ruby Creek
Bridge	–	–	Stream	Over Tributary
Natural Crossing	Water over trail	–	Stream	5 natural crossings; Some water present
1	Corrugated Plastic	10”	Stream	Trickle; Widener upstream; Topped with boulders
2	Corrugated Plastic	10”	Stream/Drainage	Same as 1, but collects trail drainage and 90° turns
3	Corrugated Metal	18”	Stream	More trickle; boulder stream
4	Corrugated Metal	24”	Stream/Drainage	Trickle; some flow around culvert; boulders scarce; cobble downstream; some erosion downstream; wood crib on top; collecting trail drainage & seeps

Culvert #	Material	Diameter	Stream/Drainage	Comments
5	Smooth Steel	20”	Stream	Plugged inside; no water; lots of downed wood; downstream flat, landslide opportunities; some fines at inlet; *suggest replace soon*.
6 (removed)	Smooth Steel	16”-22”	Stream	Removed pipe on side of trail; natural stream crossing – stable; size depends on location measured
Drainage Crossing – Dry	None	–	–	2 natural crossings
7	Smooth Steel	18”	Stream	Dry, out flow boulders, in flow at hole, center collapsed but not plugged
8 (removed)	Smooth Steel	20”	Stream	Removed culvert – Stream crossing – natural bed, good flow, bedrock shallow – unstable slopes, filling in road from upslope side near culvert
9	Corrugated Metal	24”	Stream	Little bit of erosion on side and under
No Culvert?	None	–	–	Looks like a culvert should be here – may be plugged and buried with a sink hole entrance
10	Smooth Steel	18”-20”	Stream	Boulder stream; perched; erosion below; another buried culvert that look similar but offset upstream; parallel
11	Corrugated Metal	16”	Stream	No flow; rock, top rock; short
Natural Dry Crossing	None	–	Stream	2 natural crossings
Natural Crossing	None	–	Stream	Good flow, No culvert, “Rock Crossing”; Lots of debris
Natural, Dry Crossing	None	–	Stream	3 natural crossings
After Split (continue N. on E Bank Trail): Dry Crossing	None	–	Stream	4 natural crossings

Additional Comments

- Trail looks like old road; possible old logging/mining road? This area was the scene of gold rush in 1880s.
- Trail on hill slope, not adjacent to major stream
- Smooth steel culverts have rivets…look to be original
- After culvert #6, wider “road” thins to trail; Unstable in spots
- Almost all culverts clean inside – Young forest…Fire history?
- At 11:30 – Trail splits after 2.8 miles – We head up (north) East Bank Trail toward Hidden Hand Pass *(Other options are to Hidden Hand Campground and Jack Mountain Trail)*
- After split there was a long stretch with no culverts – gentle topography but still climbing
- 12:00 Turned around and headed back to main road

Appendix B. Culvert Inventory Data Sheet – Draft Version April 3, 2014

Office use only	*(use initials and mm/dd/yy)*
Entered by: ________	date: ________
Updated by: ________	date: ________
Verified by: ________	date: ________
Certified by: ________	date: ________

Culvert Inventory Field Data Sheet

BASIC INFORMATION

Park or Forest (*check one*): __North Cascades __Mount Rainier ___Mount Baker-Snoqualmie

Observers (*first and last names*): ____

Site (*entering road or trail name*): ____

Date (*mm/dd/yy*): ____/____/____ **Time** (*military time*): ____________________

Weather conditions: ____

Multiple structures at site *(check one):* __No __Yes *(fill out separate data sheet for each crossing)*

LOCATION

Check on the GPS unit to insure that the datum and zone are: Datum: NAD83 Zone: 10N

Field UTM X __ __ __ __ __ __ m E **Field UTM Y** __ __ __ __ __ __ __ m N **GPS error:** ______

Latitude: ______________________ N **Longitude:** ______________________ W

Elevation (*m*): _________ **Source** (*check one*): ☐ map ☐ GPS

Access type (*check one*): ☐ road ☐ trail

Name of Road or Trail (*if known*): ____

Mile Marker (*if known*): ____

PHOTOS

Photo ID	Photo Subject

GENERAL SITE CHARACTERISTICS:

Primary Site Aspect (*circle one*): N NE E SE S SW W NW

Surrounding Land Use/Land Cover (*check dominant one*):

☐ developed ☐ forest ☐ shrubs ☐ grass ☐ wetland ☐ barren ☐ water

Road/Trail surface (*check one*): ☐ paved ☐ gravel ☐ soil ☐ wood

Surface Condition (describe): ____________________

Trail Type (*check one*): ☐ closed ☐ open **Remoteness** (*check one*): ☐ High ☐ Medium ☐ Low

Crossing Type (*check one*): ☐ stream crossing ☐ drainage crossing

Condition of Crossing (*check one*): ☐ new ☐ good ☐ fair ☐ poor

Is the water flowing? (*check one*): ☐ yes ☐ no

CULVERT CHARACTERISTICS:

Culvert Shape (*check one*): ☐ Round (circular) ☐ Arch ☐ Box ☐ Oval (elliptical) ☐ Other

Does culvert have a bottom? (*check one*): ☐ Yes ☐ No (bottomless)

Culvert material

☐ Corrugated metal
☐ Smooth metal
☐ Concrete
☐ Corrugated plastic
☐ Smooth plastic
☐ Wood or log
☐ Other: ____________________

Corrugations (*check all that apply*)

☐ spiral
☐ annular (*straight*)
☐ 2 2/3 x ½ inch
☐ 3 x 1 inch (*pitch and depth*)
☐ 5 x 1 inch
☐ Other: ____________________
☐ None

Inlet type

☐ At grade – native
☐ At grade – riprap
☐ Projecting
☐ Mitered
☐ Wingwall ≤30°
☐ Wingwall >30°
☐ Headwall
☐ Apron
☐ Trash rack
☐ Other: ____________________
Describe: ____________________

Outlet type

☐ At grade – native
☐ At grade – riprap
☐ Projecting
☐ Mitered
☐ Cascade over riprap
☐ Freefall into pool
☐ Freefall onto riprap
☐ Apron
☐ Other: ____________________
Describe: ____________________
____

Baffles, weirs or other internal structures: ☐ Yes ☐ No Material: ____________________

Describe: ____________________

CULVERT DIMENSIONS

Dimensions (*meters*)

Inlet
Width: ________________
Height: ________________

Outlet
Width: ______________________
Height: ______________________

Culvert length: ____________
Rust line height: ____________
Structure shape comments: ____

Azimuth (*degrees*)
Road/trail centerline at crossing: __________
Upstream: ____________
Downstream: __________
Culvert: ______________

Slope (*degrees*)
Road/trail: __________________
Upstream: __________________
Downstream: ________________
Culvert: ____________________

Describe breaks in azimuth or slope within culvert: ____

____

Elevation (*meters*)
Road/trail surface: ______ Pipe crown at inlet: ___________ Pipe crown at outlet: __________
Headwater: ____________ Tailwater: __________

CULVERT CONDITION

Inlet condition (*check one*): ☐ submerged ☐ not submerged ☐ partially submerged *(water drops in)*

Outlet condition (*check one*): ☐ submerged ☐ not submerged ☐ partially submerged

Embedding (*check one*): ☐ Not embedded ☐ Partially embedded ☐ Fully embedded ☐ No Bottom

Substrate in structure:

☐ None
☐ Discontinuous layer – begins at: _______ m; ends at ________m (*measured from inlet*)
☐ Substrate is continuous throughout structure
If present, substrate depth at inlet ________m; substrate depth at outlet ________ m

Pipe condition:

☐ Entrance dented
☐ Debris plugging inlet (% blockage______)
☐ Debris in culvert (boulders or wood)
☐ Bottom worn through ☐ Bottom rusted through ☐ Top broke through
☐ Fill around culvert eroding
☐ Water flowing under culvert
☐ Other ___________________________

STREAM FEATURES

Armored streambed or streambanks:

At inlet: ☐ None ☐ Extensive ☐ Not extensive

At outlet: ☐ None ☐ Extensive ☐ Not extensive

Crossing span of stream:

☐ Severe constriction ☐ Mild constriction ☐ Spans bank to bank ☐ Spans channel and banks

Scour pool downstream:

☐ None ☐ Small (wider or deeper than natural stream) ☐ Large (width or depth 2X natural stream)

Sediment bars: ☐ None ☐ Upstream ☐ Downstream ☐ within culvert

For the following questions use as a reference a portion of the natural stream channel that is outside the influence of the crossing structure and not otherwise altered.

Bankfull channel widths—outside of culvert influence (*meters*):

Upstream: (1) ____________ (2) ____________ (3) ____________ Average ___________

Downstream: (1) ____________ (2) ____________ (3) ____________ Average ___________

Substrate particle sizes:

Number 1 up to 3 in order of sizes occupying most of streambed area (*1 being most common*)

	Bedrock	Boulders	Cobbles	Gravel	Sand	Silt/Clay	Organics	Aquatic Veg.
Upstream:								
Downstream:								

Culvert comparison to stream:

Water depth matches stream? ☐ Yes (comparable) ☐ No (deeper) ☐ No (shallower) ☐ Dry

Water velocity matches stream? ☐ Yes (comparable) ☐ No (slower) ☐ No (faster) ☐ Dry

Culvert slope matches stream? ☐ Yes (comparable) ☐ No (flatter) ☐ No (steeper)

Substrate matches stream? ☐ Yes (comparable) ☐ No (coarser) ☐ No (finer)

Fish observed: ☐ Yes ☐ No

Physical Barriers to fish passage: ☐ Severe ☐ Moderate ☐ Minor ☐ None

Describe: ____

Suggested Updates to Data Sheet

Section	Item	Suggestion
Basic Information	Site	Consider what this is for, why/if it is needed. Maybe nearest town or something to categorize this information.
Location	GPS Unit	If no GPS unit, smart phones can geocode location when photos are taken, which could be used to fill in location.
Photos	Photo Subject	Need to establish a coding system…like NOCAdate1
General Site Characteristics	Road/Trail Surface	Wood might be something like a boardwalk
General Site Characteristics	Trail Type	Think about where a surveyor would find this information and is remoteness a judgment call.
General Site Characteristics	Condition of Crossing	Surveyors would need guidance on how to make this judgment.

Appendix C. Example Peak Streamflow Estimation from StreamStats and VIC Future/Historic Ratio

Step 1

Go to USGS StreamStats (version 4) web page (https://water.usgs.gov/osw/streamstats/) and select *Go to the StreamStats application*. Zoom in to at least level 8 to be able to choose Washington State or the state of your choosing. Then zoom in to at least a level 15 to find your site of interest, so you can see the stream grid cells clearly. A delineation button will appear on the left and use your mouse to click within a blue stream grid cell to begin the delineation of your watershed above this point (it can take a few minutes to delineate watershed). If the stream is large, your map may zoom out to show the full extent of your watershed. An example for Boston Creek watershed is provides in Fig. C1. You can adjust the boundaries of the watershed based on your understanding of the topography using the Add Area and Remove Area under the Edit Basin bottom on the left and guiding tips on page 14 of the StreamStats User Instructions (https://water.usgs.gov/osw/streamstats/Version4UserInstructions-20170928.pdf).

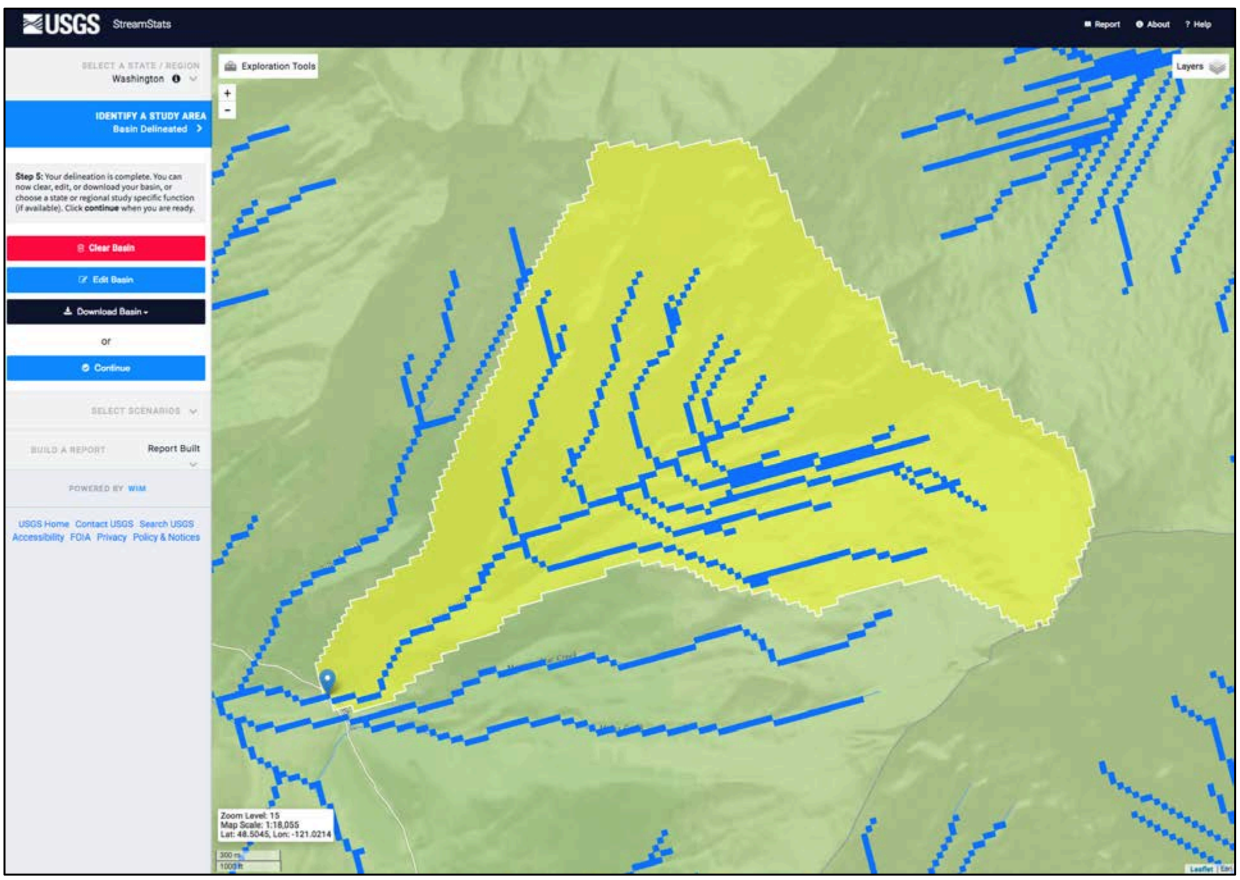


Figure C1. Delineation of watershed for Boston Creek intersection at Cascade River Road using StreamStats version 4.

Step 2

To find the basic characteristics of your basin, click on the 'Basin Characteristics' dropdown arrow and select the characteristics of interest. StreamStats then produces a 'StreamStats Report' of your basin characteristics (the ones you selected). Estimate peak streamflows based on regression equations by selecting the 'Peak-Flow Statistics' button under 'Regression Based Scenarios'. Then select all the basin characteristics desired, such as drainage area, mean elevation, and mean annual precipitation, and select the 'Continue' button. After a few moments, you can select which report you wish and the 'Continue' button. A table is created in a new window called the StreamStats Report (Fig. C2). From this information, you can see that this basin has high relief, steep slopes, and a relatively low percentage of forest cover. Another table provides estimated peak flows for several different return periods, such as 2 years, 10 years, 25 years, 50 years, 100 years, and 500 years (e.g., *PK100* for 100 years in the example below) (Fig. C3). The *basin characteristics* is also useful for providing basin traits of interest for your watershed, such as latitude and longitude, area [mi^2], elevation, and mean slope [%].

Basin Characteristics

Parameter Code	Parameter Description	Value	Unit
DRNAREA	Area that drains to a point on a stream	1.88	square miles
ELEV	Mean Basin Elevation	6480	feet
BSLDEM30M	Mean basin slope computed from 30 m DEM	59.8	percent
NFSL30	North-Facing Slopes Greater Than 30 Percent	1	
PRECIP	Mean Annual Precipitation	141	inches
SLOP30_30M	Percent area with slopes greater than 30 percent from 30-meter DEM.	96.8	percent
MINBELEV	Minimum basin elevation	2910	feet
ELEVMAX	Maximum basin elevation	8790	feet
CANOPY_PCT	Percentage of drainage area covered by canopy as described in OK SIR 2009_5267	14.9	percent
RELIEF	Maximum - minimum elevation	5880	feet

Figure C2. StreamStats report summarizing basin characteristics selected by the user.

USGS
Washington StreamStats

Print

Streamstats Ungaged Site Report

Date: Mon Apr 6 2015 10:42:21 Mountain Daylight Time
Site Location: Washington
NAD27 Latitude: 48.4878 (48 29 16)
NAD27 Longitude: -121.0838 (-121 05 02)
NAD83 Latitude: 48.4877 (48 29 16)
NAD83 Longitude: -121.0850 (-121 05 06)
Drainage Area: 1.88 mi2

Peak-Flow Basin Characteristics

100% Region 2 (1.88 mi2)

Parameter	Value	Regression Equation Valid Range	
		Min	Max
Drainage Area (square miles)	1.88	0.08	3020
Mean Annual Precipitation (inches)	141	23	170

Peak-Flow Streamflow Statistics

Statistic	Flow (ft^3/s)	Standard Error (percent)	Equivalent years of record	90-Percent Prediction Interval	
				Minimum	Maximum
PK2	275	56	1		
PK10	528	53	1		
PK25	667	53	2		
PK50	801	53	2		
PK100	909	54	3		
PK500	1230				

Figure C3. StreamStats Report for Boston Creek watershed where it crosses Cascade River Road including basin characteristics table and estimate peak-flow statistics table. Note that the peak-flow statistics table will be updated with the new StreamStats version 4.

Step 3

Identify where your stream crossing is located on the VIC ID Map (Fig. C4) and note the grid cell code.

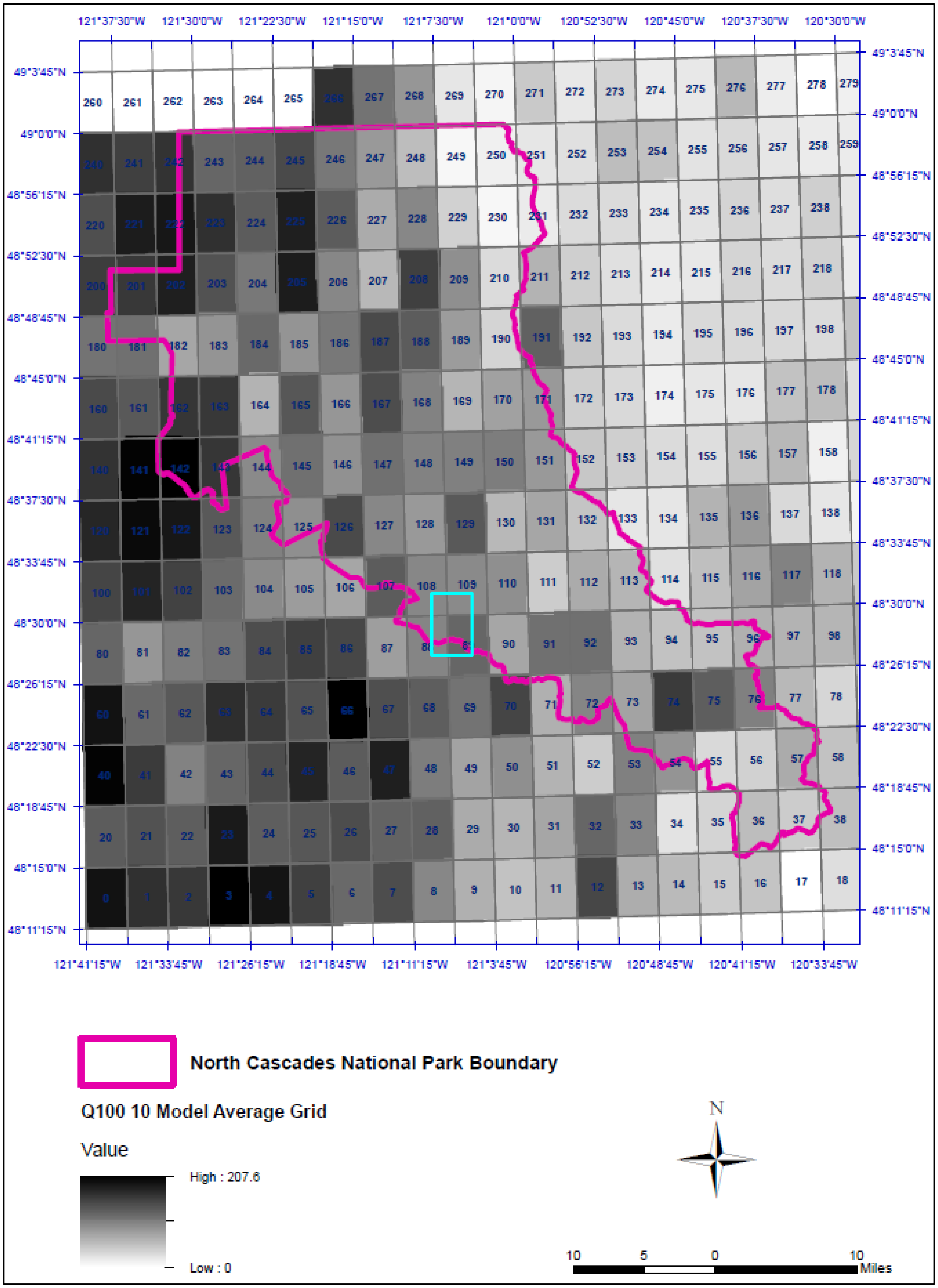
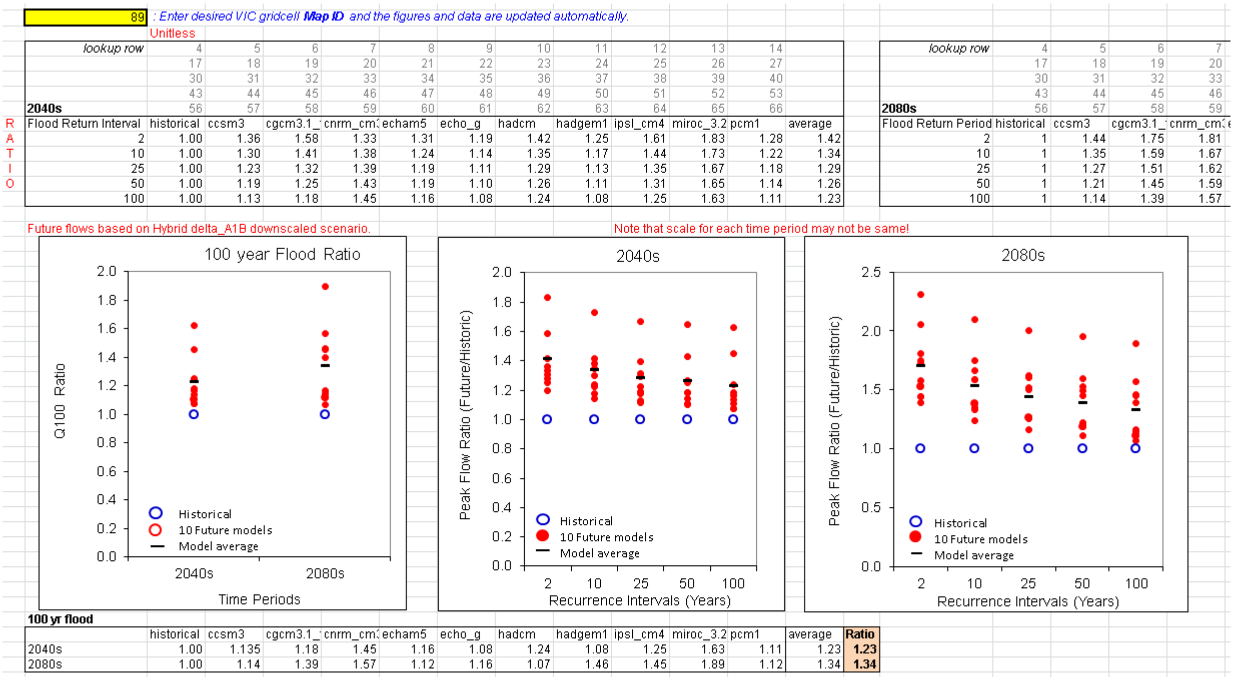


Figure C4. VIC ID Map that provides the reference grid cell code corresponding to VIC streamflow information provided in Excel spreadsheets. Cell (#89) containing the stream crossing is highlighted.

Step 4

Open the Excel spreadsheet that contains the VIC future/historic *ratios* of streamflow (Fig. C5). Enter the map code into the yellow box and note the update of three figures below (e.g., grid cell ID 89). Select the streamflow recurrence interval (e.g., 100 years) of interest and identify the ratio corresponding to that recurrence interval and future time period of interests (e.g., 2040s) at bottom.



89 : Enter desired VIC gridcell **Map ID** and the figures and data are updated automatically.

Unitless

lookup row	4	5	6	7	8	9	10	11	12	13	14	
	17	18	19	20	21	22	23	24	25	26	27	
	30	31	32	33	34	35	36	37	38	39	40	
	43	44	45	46	47	48	49	50	51	52	53	
2040s	56	57	58	59	60	61	62	63	64	65	66	
Flood Return Interval	historical	ccsm3	cgcm3.1_	cnrm_cm	echam5	echo_g	hadcm	hadgem1	ipsl_cm4	miroc_3.2	pcm1	average
2	1.00	1.36	1.58	1.33	1.31	1.19	1.42	1.25	1.61	1.83	1.28	1.42
10	1.00	1.30	1.41	1.38	1.24	1.14	1.35	1.17	1.44	1.73	1.22	1.34
25	1.00	1.23	1.32	1.39	1.19	1.11	1.29	1.13	1.35	1.67	1.18	1.29
50	1.00	1.19	1.25	1.43	1.19	1.10	1.26	1.11	1.31	1.65	1.14	1.26
100	1.00	1.13	1.18	1.45	1.16	1.08	1.24	1.08	1.25	1.63	1.11	1.23

lookup row	4	5	6	7
	17	18	19	20
	30	31	32	33
	43	44	45	46
2080s	56	57	58	59
Flood Return Period	historical	ccsm3	cgcm3.1_	cnrm_cm
2	1	1.44	1.75	1.81
10	1	1.35	1.59	1.67
25	1	1.27	1.51	1.62
50	1	1.21	1.45	1.59
100	1	1.14	1.39	1.57

100 yr flood

	historical	ccsm3	cgcm3.1_	cnrm_cm	echam5	echo_g	hadcm	hadgem1	ipsl_cm4	miroc_3.2	pcm1	average	**Ratio**
2040s	1.00	1.135	1.18	1.45	1.16	1.08	1.24	1.08	1.25	1.63	1.11	1.23	**1.23**
2080s	1.00	1.14	1.39	1.57	1.12	1.16	1.07	1.46	1.45	1.89	1.12	1.34	**1.34**

Figure C5. Excel spreadsheet with the ratio of future to historic peak flows simulated by the VIC hydrologic model as well as summary plots for different flow recurrence intervals and future time periods.

Step 5

Multiply the VIC ratio by the StreamStats magnitude to obtain an adjusted peak streamflow magnitude to use in performance assessments or design. For example, the 2040s Q100 ratio for grid cell 89 is 1.23. Multiplying this ratio by the Q100 streamflow magnitude in the table in Fig. C3 of 909 cfs would result in 1118 cfs by 2040s (23% increase), and 1218 cfs by 2080s (ratio 1.34), or a 34% increase.

The Department of the Interior protects and manages the nation’s natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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