Introduction and Project Overview

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Project Overview

The full title of the research project described in this report is: “A Comprehensive Hydrologic Data Base Incorporating IPCC Climate Change Scenarios to Support Long-Range Water Planning in the Columbia River Basin”. For the remainder of the report we will refer to the project using the abbreviated title “The Columbia Basin Climate Change Scenarios Project” (CBCCSP). The project is a collaborative venture between the University of Washington Climate Impacts Group and five regional study partners. Primary funding for the project was provided by the Washington State Department of Ecology via Washington State House Bill 2860 (HB2860). Supplemental funding was provided by four additional regional study partners:

- The Bonneville Power Administration
- The Northwest Power and Conservation Council
- Oregon Water Resources Department
- British Columbia Ministry of the Environment

The Pacific Climate Impacts Consortium at the University of Victoria, BC provided in kind support and funding for collaborative research which contributed materially to this project. Additional study partnerships (without financial support) include:

- Montana Department of Natural Resources
- Idaho Department of Water Resources
- US Bureau of Reclamation, Boise Regional Office
- US Army Corps of Engineers, Seattle and Portland Districts

As discussed in more detail below, the primary objective of the project is to provide a comprehensive and up-to-date database of simulated hydrologic data incorporating climate change information from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report to support of long-term water resources planning in the Pacific Northwest Columbia River basin.

1. Background and Motivation for the Project

As the scientific consensus on the nature of global climate change and public awareness of the impacts of climate change on western water resources has grown in recent years, the need to incorporate climate change scenarios in water planning efforts and policy decisions has been widely acknowledged in the West, perhaps most notably in California.

Here in the Pacific Northwest (PNW), although a number of pilot water planning efforts incorporating climate change have been carried out for specific water resources systems in the past five years or so, currently there is no comprehensive, up-to-date, self-consistent and publicly available source of hydrologic scenarios incorporating climate change information available to guide water planners and policy makers in the PNW. In the PNW Columbia River basin, the lack of appropriate hydrologic scenarios quantifying the impacts of regional climate change on water resources has generated particularly great concern because the region is currently investing, on a large scale, in comprehensive water resources planning efforts for the Columbia associated with salmon restoration, water supply, flood control, hydropower production, and the complex transboundary relationship between Canada and the US. Despite a growing awareness that climate change is likely to significantly impact the success of these planning efforts, the lack of water planning scenarios that reflect expected changes in climate for the 21st century has been a formidable obstacle to incorporating climate change information into water planning efforts and related policy decisions.

One of the central challenges of producing a set of comprehensive and self-consistent climate change streamflow scenarios for the Columbia basin is that water planning must be conducted at a wide range of spatial scales from relatively small-scale studies for individual sub-basins of the Columbia (e.g. the Yakima and Okanogan basins) to large scale studies encompassing the entire Columbia basin (e.g. for system-wide flood control and regional hydropower planning). Fine-scale hydrologic models are effective tools for providing detailed hydrologic information at the watershed scale, but are prohibitively expensive to implement and run over the continental scales that are needed for basin-wide planning efforts. Previous large-scale modeling efforts for the Columbia (e.g. 1/8th degree latitude longitude resolution hydrologic simulations used to support pilot planning studies at the NW Power and Conservation Council) have been successful at providing useful climate change scenarios for large-scale planning, but have limited ability to accurately resolve smaller sub-basins of interest to other stakeholders.

Estimating the effects of regulation and diversions on river flows is also an important element of water resources planning. For main-stem planning and for some subbasins, sophisticated water resources models are available to estimate these effects. In these cases naturalized flow scenarios are needed for planning. Many smaller watersheds, however, currently do not have access to simulation models of this type, and scenarios of estimated "regulated" flows would be valuable.

The project has implemented improved technical methods and models and a scope of work designed to produce a comprehensive hydrologic data base for the entire Columbia River basin, providing climate change planning scenarios appropriate for both basin-wide planning efforts and more detailed planning studies in moderate and small sub-basins. In addition, pilot studies for four different basins (including the Methow, Walla Walla, Upper Yakima, and Upper Kettle) using fine scale hydrologic models are included in the study to help assess the potential advantages of implementing these more costly approaches in small-scale watersheds.

2. Overview of Study Approach and Methods:

The methods developed for the study incorporate a number of important improvements in the hydrologic models and the scenario generation process. The most important of these changes is the increased spatial resolution of the macro-scale hydrologic model (Chapter 5, this report), however important improvements in the downscaling procedures used to translate GCM simulations to driving data for the hydrologic models were also developed especially for this project to support daily time step analysis at the finer spatial scales incorporated in this project (Chapter 6, this report).

Another important component of climate change research designed to support water planning and adaptation is that it will require frequent updating with each successive IPCC assessment effort to reflect the improved understanding of impacts. Although the primary objective of the research in this proposal is the creation of hydrologic data bases to support long-range planning in the next five years or so, an important secondary objective of the project is to construct and archive a set of calibrated hydrologic models and end-to-end data processing code to allow relatively rapid updates of the hydrologic data bases on an ongoing basis.

The primary final products of this project are a set of hydrologic databases encompassing 297 streamflow locations (Chapter 8, this report), and a web site (URL) for serving these data resources to a diverse user community (Chapter 2, this report). This report is intended to serve both as a technical resource and a user's guide for the project. Additional information and detailed instructions for accessing the project databases are also available on the study website (URL).

3. Acknowledgements

This project has involved a very large group of academic researchers, management and agency professionals, and basin stakeholders. A detailed acknowledgement of all the participants would fill many pages, but here at least is a listing of some key participants in the study by affiliation:

WA State Department of Ecology
Hedia Adelsman
Ken Slattery
Kurt Unger

Bonneville Power Administration
Nancy Stephan

Northwest Power and Conservation Council
John Fazio

Jim Ruff

Oregon Water Resources Department
Barry Norris
Ken Stahr

BC Ministry of the Environment
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Dennis P. Lettenmaier
Jeremy Littell
Guillaume Mauger
Nate Mantua
Ed Miles
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Rob Norheim
Erin Rogers
Eric Salathé
Amy Snover
Ingrid Tohver
Andy Wood

US Bureau of Reclamation
- Levi Brekke
- Pat McGrane
- John Roache

US Army Corps of Engineers
- Carolyn Fitzgerald (Seattle District)
- Seshu Vaddey (Portland District)
- Randy Wortman (Portland District)

Assessing Pacific Northwest Water Resources Stakeholder Data Needs

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1. Introduction

Throughout the western U.S., the need to incorporate climate change information in water resource planning efforts and decisions has been widely acknowledged (Rayner et al., 2005; Callahan et al., 1999). However, appropriate tools, including hydrologic scenarios incorporating climate change, are often not available to water planners and policy makers to effectively guide decision making at the basin and sub-basin scale. Several studies have noted the challenge of developing climate change information that is appropriate for and integrated into decision making by water planners and policy makers (Callahan et al., 1999; Jacobs et al., 2005; McNie, 2007). Existing barriers include difficulties recognizing the utility of the information generated and institutional management resistance.

Improved communication between researchers and data users is repeatedly cited as a key element to generating information relevant and useful to decision makers (Callahan et al., 1999; Jacobs et al., 2005; McNie, 2007). Increasing communication with data users and stakeholders in research tool development, interpreting data resources, and demonstrating data utility can aid the development of appropriate and usable information for stakeholders (Callahan et al., 1999). More often, when research products have not been developed with stakeholder input, the specific needs of users go unmet (McNie, 2007).

Recognizing this, the Climate Impacts Group (CIG) surveyed stakeholders in order to ensure that the research and web products developed as part of the Columbia Basin Climate Change Scenarios Project (CBCCSP) appropriately matched user data needs. This report summarizes the results of that survey.

2. Approach/Methods

The CBCCSP data needs survey took place between October and December 2007 using the SurveyMonkey.com online survey tool. Survey participants were solicited via the CIG's listserve and through regional contacts at various meetings, including the CIG's annual climate and water fall forecast meetings. A total of 178 respondents completed some portion of the online survey.

The survey consisted of 11 questions designed to assess the data users, their data needs, and data delivery preferences (Table 1). Four additional optional questions asked for perspectives on organizational capacity to adapt to climate change. Survey questions included a mix of multiple choice and open-ended response questions. Response rates for individual questions ranged from 21-99%.

Table 1. Survey questions and response rates

Question	Question type/Response options	Response Rate
1. What organization/agency do you work for?	Open response	144/178 (81%)
2. What specific geographic areas of the Pacific Northwest are important to your occupational activities?	Multiple choice with open response option: 63 geographic regions + Other	176/178 (99%)
3. What specific management areas are you involved with?	Multiple choice with open response options: Hydropower, instream flow management, water supply, navigation, irrigation supply, hatchery management, recreation, other.	176/178 (99%)
4. What specific occupational activities are you involved with?	Multiple choice with open response options: Resource management, watershed or ecosystem restoration, long-range planning, operations, policy making, other.	176/178 (99%)
5. From the following list of meteorological and hydrological variables, which would be useful to you in the context of planning for a changing climate?	Multiple choice • *1/16th degree gridded data* - Total precipitation, max. temperature, runoff, min. temperature, baseflow, snow water equivalent (SWE), fraction of precipitation as rain, date of peak SWE, date of 90% SWE melt, potential evapotranspiration (ET), total column soil moisture, natural ET, tall crop ET, short crop ET. • *Time-step choices:* hourly, daily, weekly, twice-monthly, monthly.	150/178 (84%)
6. (Same as #5 but for streamflow and water temperature data)	Multiple choice • *Streamflow data:* Streamflow, water temperature • *Time-step choices:* hourly, daily, weekly, twice-monthly, monthly	146/178 (82%)
7. Are there additional hydrological or meteorological variables that	Open response	38/178 (21%)

would be useful to you that are not included in the above list?		
8. What other kinds of information or products derived from the above data would be useful to you in planning for or adapting to climate change impacts? (e.g. spatial maps of changes in the mean?)	Open response	43/178 (24%)
9. How do you prefer to acquire electronic data?	Multiple choice with open response option: Conventional web services (e.g. html pages), FTP sites (download files via the web), CDs, electronic reports, paper reports, Other	133/178 (75%)
10. What file formats do you prefer for data?	Multiple choice with open response option: ASCII (text) files, conventional binary format, Excel spreadsheets, netCDF, Other)	135/178 (76%)
11. What documentation should be prepared to make available data resources most useful?	Open response	135/178 (76%)
Supplemental Adaptation Questions		
12. How has interest in including climate change information in your organizations planning changed in recent years? What (if any) specific events or types of information have led to this change?	Open response	49/178 (28%)
13. How do you expect climate change will affect your organization's interests and responsibilities?	Open response	83/178 (47%)
14. How would you rate your organization's capacity to integrate climate change data and information into planning and management activities? Why did you give it that ranking?	Multiple choice: Excellent, good, fair, or poor with open response option for second part of question	127/178 (71%)
15. What would increase your organization's ability to adapt to climate change?	Open response	84/178 (47%)

3. Key Findings: Survey Responses

3.1 Data Users *(Questions 1-4)*

Survey participants were involved in water resource management through a wide range of organizations and management activities across the Pacific Northwest (PNW) region (questions 1 and 3). State and federal agency staff made up 60% of survey participants, with the remainder represented by staff from private sector, local government, tribal, non-governmental (NGO), and academic organizations (Figure 1). Water supply, instream flow management, and hydropower production were the dominant management areas for survey participants, followed by irrigation supply and recreation (Figure 2).

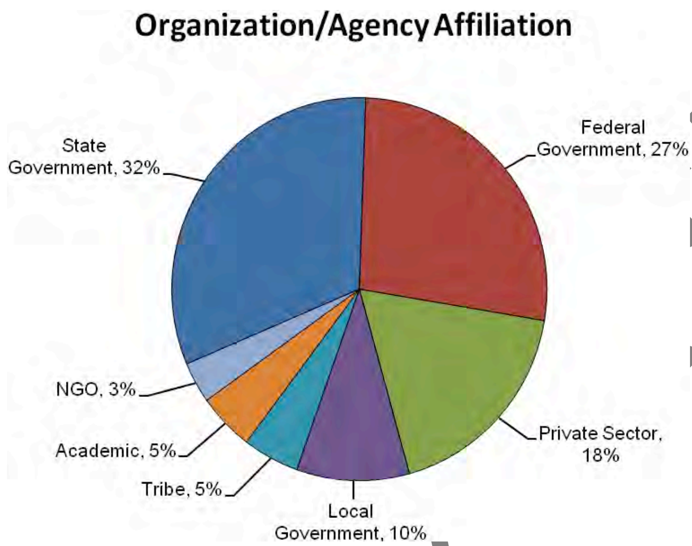

Figure 1. General organization/agency affiliation of survey participants

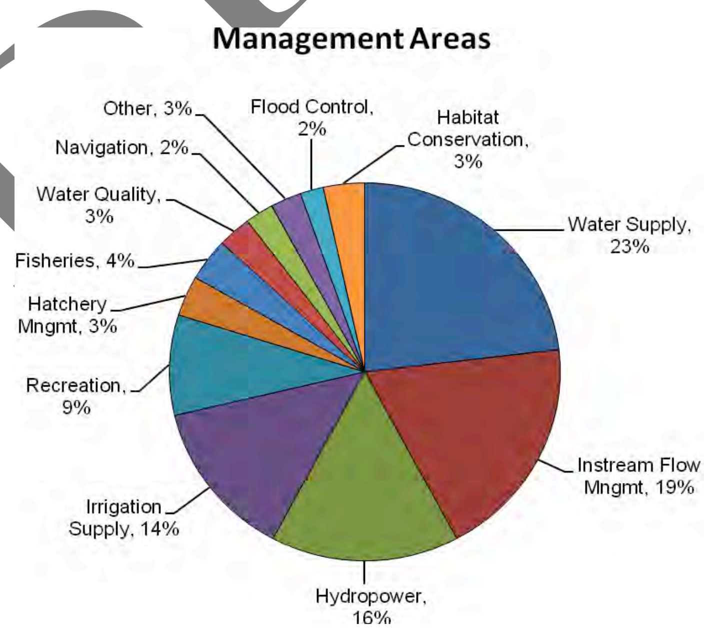

Figure 2. Management areas of survey participants

Respondents identified over 78 different geographic regions throughout the PNW as important to their occupational activities (question 2). Nearly half of the participants indicated the importance of the entire PNW region or Columbia River Basin in their management activities. Eastern Washington basins dominated the top 30 responses, although "Other" responses, which ranked third in total count, included numerous Idaho and Oregon basins. The Lower Snake, Lower Yakima, Upper Yakima, Middle Snake, and Okanogan regions - all arid regions with significant water management needs - were each identified as important to 15% or more of the 176 survey participants responding to this question. Other basins selected by 10% or more of respondents included but were not limited to: Grand Coulee (13%), Wenatchee (13%), Methow (12%), Naches (12%), Lower Crab (11%), Walla Walla (11%), Entiat (11%), Kettle (11%), Chelan (10%), and the Upper Skagit (10%). These geographic interest areas match well with the streamflow locations ultimately selected for the database (Figure 2, Chapter 8).

3.2 Data Needs *(Questions 5-8)*

The main product of the CBCCSP is a web-based data visualization and delivery system that provides stakeholders, researchers, and the general public with free access to the data products. Both the comprehensive hydrologic data base and downscaled climate scenario projections developed by the CIG provide increased spatial resolution relative to existing resources by using 1/16th degree (approximately 12.5 sq. mi. or 36 sq. km) gridded data resolution. The data need priorities identified by the survey respondents provided direct feedback for the design and development of the database and web-based products.

Data need preferences for 1/16th degree gridded data resolution (question 5) were remarkably uniform throughout different management areas. The most requested variable among survey participants was total precipitation (requested by 92% of question respondents) followed by maximum temperature (91%), runoff (87%), minimum temperature (86%), and baseflow (79%) (Figure 3). Survey participants overwhelmingly preferred data at a daily time step (42%); monthly was the next most requested time step (21%). This result confirmed the CIG's decision to provide analysis at a daily time step, which was based on previous observations that this planning element had received limited attention in past downscaling efforts (Hamlet and Snover, 2007).

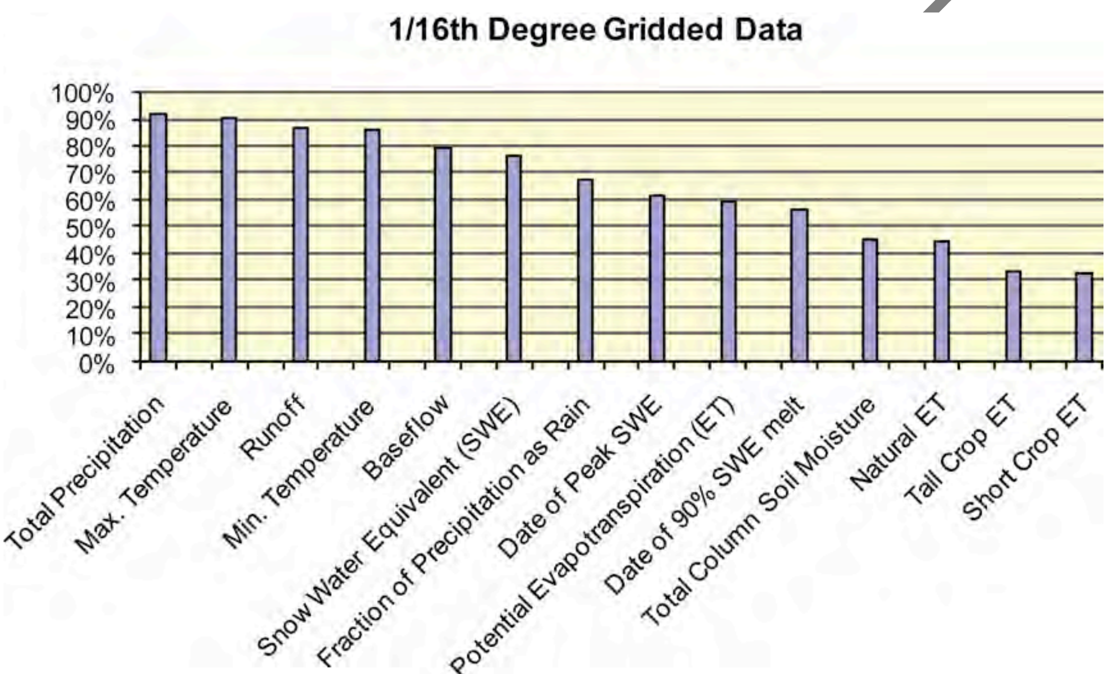

Figure 3. Overall ranking of 1/16th degree gridded variables by survey respondents.

The ranking of each variable's utility within leading management areas is shown in Table 2. For example, while total precipitation was the most requested gridded data variable among all survey participants (and daily the most requested time step for total precipitation), daily total precipitation ranked as the fifth most requested variable for water supply managers. With only a few exceptions, survey respondents from all management areas selected the same top ten data variables, differing only in their order of preference.

Table 2. Top 10 requested 1/16th degree gridded meteorological and hydrological variables sorted by leading management areas of survey participants. Although time step was not a factor in the ranking, the daily time step was the preferred time step choice for each of the top 10 requested data variables.

Data Variable, *ranked in order to total preference*	**Preferred Time Step**	**Water Supply**	**Instream flow mngmt**	**Hydro-power**	**Irrigation Supply**
1. Total Precipitation	Daily	5	5	4	6
2. Maximum Temperature	Daily	1	1	1	2
3. Runoff	Daily	2	2	3	1
4. Minimum Temperature	Daily	2	3	2	3
5. Baseflow	Daily	5	5	4	5
6. Snow Water Equivalent (SWE)	Daily	4	4	6	3
7. Fraction of Precipitation as Rain	Daily	8	7	7	7
8. Date of Peak SWE	Daily	7	8	8	9
9. Potential Evapotranspiration (ET)	Daily	10	10	10	8
10. Date of 90% SWE melt	Daily	8	9	9	10

Streamflow and water temperature data ranked high for respondents (question 6). Ninety-seven percent of respondents requested streamflow data and 76% requested water temperature data. As with other variables, respondents preferred the daily step over other time steps although hourly was a close second (36% versus 34%, respectively).

Questions 7 and 8 were open response questions asking for additional data variables and derived information products that would be useful. Although response rates were low for both questions (21% and 24% respectively), both questions provided valuable information. Additional suggested data variables included wind speed and direction, air temperature, relative humidity, turbidity, solar radiation, snow pack characteristics (e.g. snow depth, snowpack temperature) and additional streamflow characteristics (e.g. peak flow, canal flow). Many of these are included in the suite of variables offered to website users. Suggested derived products included spatial maps of data anomalies/patterns of mean changes such as changes in seasonal or inter-annual variability, peak flow timing, daily extremes (including extreme precipitation), and monthly runoff patterns compared to historic patterns. These products would serve as useful information products in planning for or adapting to climate change impacts. Several respondents indicated that spatial maps would be especially valuable for communicating information to the public.

3.3 Survey Responses: Data Delivery Preferences *(Questions 9-11)*

Survey respondents had clear preferences regarding data delivery formats (questions 9 and 10). Respondents overwhelmingly indicated a preference for receiving data via conventional web services (82%) or FTP sites (63%) over the use of CDs or paper reports. Additionally, respondents preferred Excel spreadsheets (83%) or ASCII (text) files (62%) over other file formats such as conventional binary format or net CDF.

Survey participants also provided a variety of suggestions regarding what types of documentation would make the available data resources most useful (question 11). Metadata - information that describes data, including information on data sources, definition of data variables, data collection methods, data manager contact information, data confidence and relevant assumptions - was requested. One respondent noted that the metadata that accompanies USGS stream gauge network is a useful model of appropriate data documentation. Data descriptions including short non-technical synopsis reports, summary tables, and data interpretation were also suggested.

3.4 Survey Responses: Perspectives on Integrating Climate Change Information *(Questions 12-15)*

Survey respondents, at a lower response rate, provided their perspectives on the integration of climate change information at their respective organizations through a series of mostly open-ended supplemental questions focused on adaptation. Responses indicate a growing interest in and recognition of climate change (question 12). Just over half (54%) of 49 respondents indicated increasing interest in climate change within their organizations, 31% cited that climate change information is being included in planning efforts, and 19% cited that management has made climate change a greater priority. Primary drivers of this increased interest included: a growing awareness of the problem sparked by specific climatic events such as regional drought and forest fires, or observed changes (e.g., earlier runoff event, rising surface water temperature); increased media coverage of climate change; increased knowledge of impacts by the general public; the availability of studies integrating climate change; presentations on climate change impacts; and attendance at climate change workshops. In one case, interest was driven by an organizational requirement to include climate change in planning.

Increased interest in climate change paralleled a strong recognition by 93% of respondents that climate change will affect the interests and responsibilities of organizations to varying degrees (question 13). About one-third (31%) of respondents expected reduced resource availability. Other expected changes - potentially driven by reduced resource availability - included changes in decision making and planning (21%), regulatory changes (21%), and the need to include climate change information in analysis (12%).

Despite the widespread recognition of potential impacts on their organizations activities, most respondents do not feel their organizations currently have the capacity necessary to integrate climate change information and data into planning and management activities (question 14). When asked to rank the capacity of their organization, 56% of 127 respondents gave a Fair or Poor ranking. Furthermore nearly three times as many negative justifications were provided for the selected rankings as compared to existing positive attributes. Responses highlighted several organizational barriers including any or all of the following: limited staff capacity, lack of clear guidance on how to integrate climate change into planning, lack of management support, institutional inertia, limited data availability, limited funding, lack of a mandate to plan for climate change, and complexity of the problem. For the 44% of respondents who rated their organization's capacity as Good or Excellent, reasons cited included existing use of climate information, good access to climate data, staff expertise, and a clearly demonstrated priority of dealing with climate change.

Current limitations clearly drove responses to question 15, which asked respondents to identify those things that would increase their organization's ability to adapt to climate change (Figure 4). Proposed strategies included both "top down" institutional needs as well as "bottom up" needs from staff and outside resources. Top down institutional needs included the need for a clear mandate (10%) and more funding (14%) or staff capacity (5%) dedicated to climate change. "Bottom up" needs included new data and/or more site specific data (21%), improved organizational understanding of climate change impacts (15%), improved communication/coordination on climate change issues within the organization (8%), and improved access to data (6%). While the "top down" institutional needs are beyond the scope of CIG's current research efforts, the CBCCSP directly addresses several of the "bottom up" needs.

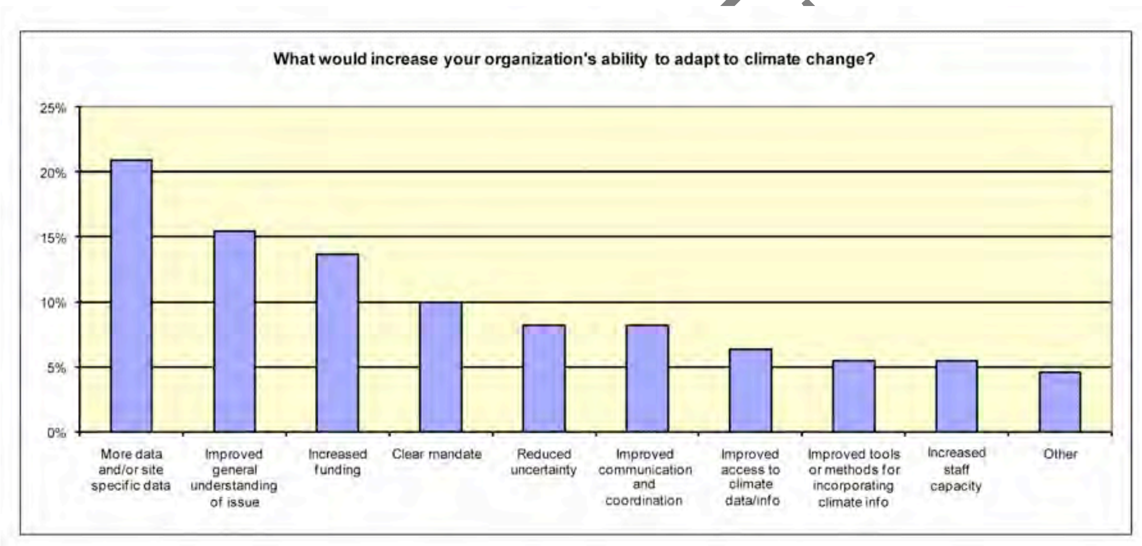

Figure 4. Increasing organizational capacity to adapt to climate change

4. Conclusions

Incorporating stakeholder input generated from the CBCCSP survey has enhanced the utility of research and web products developed from CIG's research efforts for water planners and policy makers. Survey respondents represented a wide array of organizations, agencies, and management areas, providing a valuable range of stakeholder input. In several areas, survey responses provided clear recommendations for the design of CIG's research products. Geographic areas of importance reflected the management priorities of survey respondents. Data provided at a daily time step and in accessible Excel or ASCII (text) file formats through conventional web services were strongly preferred by respondents across all management areas. Spatial maps and metadata accompanying data sets were recommended by respondents as useful tools for incorporating this information into planning for and adapting to climate change.

Incorporating these design elements into the CBCCSP research and web products efforts will address strategies proposed by stakeholders to enhance the capacity of their organizations to prepare for climate change by improving access to climate date and information, improving the ability to integrate data into analysis, and improve understanding of the issue. Beyond these efforts, stakeholders identified clear barriers that still remain to effectively plan for and adapt to climate change, including the need for greater funding and staff resources as well as a clearer organizational mandate to address climate change.

5. References

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Historical Meteorological Driving Data Set

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1. Introduction

Spatially distributed and temporally complete precipitation, temperature, and wind datasets are needed to drive hydrologic models used in investigations of the impacts of observed, and projected future, climatic change in the Pacific Northwest. Prior observation and modeling efforts, for example, have demonstrated regional temperature shifts of about 0.8°C over the 20th century, with projected temperature increases of 1.5-3.2°C by mid 21st century (Mote *et al.*, 2003). Although not attributable to a change in greenhouse forcing, precipitation has also changed markedly in the 20th century, and future projections point to wetter winters and drier summers (Mote and Salathé 2009). These kinds of changes have important hydrologic and water management implications in the PNW (Hamlet and Lettenmaier 1999; Snover et al. 2003; Payne et al. 2004; Elsner et al. 2009; Hamlet e t al. 2009; Vano et al. 2009).

The importance of large-scale studies not withstanding, increasingly, policy makers and water management professionals require local, or basin-specific assessments and forecasts for development of climate impact adaptation strategies. In general these needs can be met using existing modeling approaches, but require hydrologic models and meteorological driving data sets at higher spatial resolution. For the CBCCSP described in this report, the spatial resolution of the macro-scale VIC hydrologic model has been increased to 1/16th degree latitude/longitude resolution to help better resolve smaller basins included in the study (Elsner et al. 2009; Chapter 1 introduction, Chapter 5,6 covering hydrologic modeling).

Starting with methods developed by Maurer et al. (2002), Hamlet and Lettenmaier (2005) developed methods to regrid National Climatic Data Center (NDDC) Cooperative Observer (COOP) network and Environment Canada (EC) station data to produce daily time-step hydrologic forcings covering the time period of 1915 - 2003 at a spatial resolution of 1/8th degree. Their methods incorporate U.S. Historical Climatology Network (HCN) and Historical Canadian Climate Database (HCCD) data to correct for temporal biases caused by inhomogeneities in the COOP station assemblages through time, and use the Precipitation Regression on Independent Slopes (PRISM; Daly *et al.*, 1994; 2002) monthly normals to scale precipitation for orographic influences. These driving datasets have been used as driving data for the Variable Infiltration Capacity (VIC) hydrologic model over the western U.S. Results from these studies have been used to describe regional climatic trends and their hydrologic implications (see Mote et al. 2005; Hamlet et al. 2005; Hamlet et al. 2007; Hamlet and Lettenmaier 2007),

For the Columbia Basin Climate Change Scenarios Project, the methods of Hamlet and Lettenmaier (2005) have been extended and improved to:

- double the spatial resolution to 1/16th degree,
- implement temperature rescaling via PRISM monthly normals,
- cover the time period 1915-2006

Several other minor improvements in the methods have also been implemented as discussed below. This paper describes the methods used in constructing the meteorological data sets used in the study.

2. Approach and Methods

2.1. Sources of data

NCDC COOP and EC daily time step station data are the primary sources for precipitation and temperature observations used in creating the daily time-step forcing series for the Pacific Northwest (PNW) domain, which encompasses the entire Columbia River drainage system, along with the basins west of the Cascade Range (Figure 1). HCN and HCCD data are used as monthly time step benchmarks to maintain temporal consistency and remove biases generated from the regridding of the daily station data. In contrast to Hamlet and Lettenmaier (2005), the Adjusted Historical Canadian Climate Database (AHCCD) network is used instead of the HCCD. The AHCCD data has been subjected to greater quality control and homogenization than the original HCCD dataset. Precipitation has been adjusted for gauge type and undercatch (Mekis and Hogg, 1999), and temperatures have been adjusted for station relocations and changes in measurement procedures (Vincent *et al.*, 2002). Maps of PRISM monthly precipitation and temperature climate normals (Daly *et al.*, 1994; 2002) allow topographic adjustment of precipitation and temperature values.

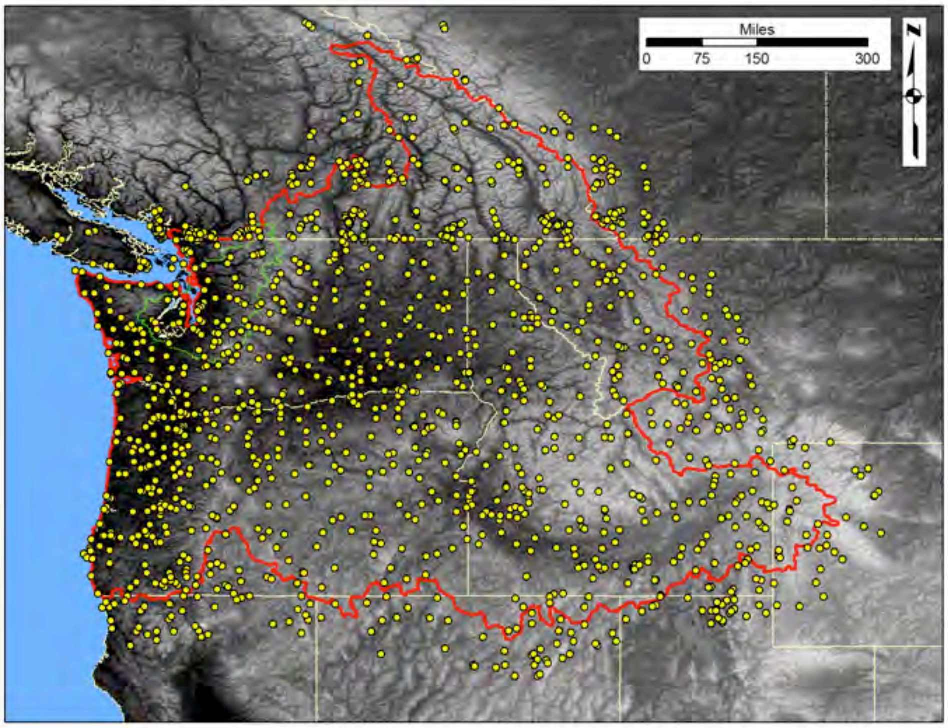

Figure 1. Map of Co-Op station locations used in creating gridded meteorological records for the Pacific Northwest. Outline in red show the study domain encompassing the Columbia River basin and coastal drainages in Washington and Oregon.

2.2. Preprocessing, quality control, and gridding

The raw COOP station data were first checked for outlier values and minimum continuity requirements. As per Hamlet and Lettenmaier (2005), any PRCP values greater than 350 mm/day were deemed higher than the climatological limit and assigned the missing data value. TMAX values higher than 55°C and TMIN values lower than -55°C were also assigned the missing data value. Stations with less than 5 years total data record, or without at least 365 continuous days of data were also removed from the dataset.

The raw COOP data records also contain quality control flags for each recorded value. Individual observations were included only if the corresponding flags indicated valid data, otherwise the observation was changed to a missing data value. Some PRCP records have several days of missing data, followed by a day flagged as an "accumulated" value. In these instances, the accumulated precipitation value was evenly redistributed over all of the preceding days with missing data. Though this method may underestimate the temporal variability of precipitation over the missing data period, it was felt to be superior to simply removing the accumulated value or allowing it to remain in the dataset as-is.

Following the quality control steps, the raw COOP station data were interpolated to a 1/16th degree grid using the Symap algorithm (Sheppard, 1984, as per Maurer *et al.* 2002; Hamlet and Lettenmaier 2005) with four nearest neighbors. TMAX and TMIN were adjusted for the elevation difference between the nearest neighbor stations and the target cell using the standard atmospheric pseudoadiabatic lapse rate of 6.1°C/km (Barry, 1992). The HCN and AHCCD data were also interpolated using the same scheme, but with 15 nearest neighbors for PRCP to avoid sharp spatial discontinuities induced by the lower station density in these networks.

One potential side effect of the regridding scheme is the occasional inversion of daily TMAX and TMIN values. This situation can occur when TMAX exhibits greater spatial or temporal variability than does TMIN or when a station is missing a TMAX or TMIN value at a particular time step and the two variables are interpolated from different station patterns (Figure 2). These daily inversions were addressed during the topographic adjustment steps, as described below.

2.3. Temporal adjustments

After the initial spatial interpolation, the methods of Hamlet and Lettenmaier (2005) were followed to correct the COOP data for temporal inhomogeneities created by changes in the station assemblages used for interpolation. The roster of active stations at each time step varies due to incomplete station records and/or the period of operation for individual stations. The interpolation scheme uses a minimum number of nearest neighbors for each interpolated value, and therefore will occasionally include information from stations that exhibit statistics substantially different from the other neighbors. This process can potentially introduce bias to the resulting time series, especially in time periods or areas with a sparse COOP station network.

In order to correct for these temporal inhomogeneities, the daily COOP values were adjusted such that the monthly average matches the gridded monthly HCN/HCCD values, following the basic approach outlined by Hamlet and Lettenmaier (2005). A minor change to the methods was implemented, however, by forcing the monthly COOP values to exactly match the monthly HCN/HCCD values without temporal filtering. This change was made to avoid the introduction of bias in isolated cases when station dropouts of one month or less occurred in the time series. Thus the final product is a hybrid derived from two different data sets. The methods preserve the low frequency (monthly) fluctuations derived from the HCN and HCCD gridded data sets, while retaining important elements of the high frequency (daily) variability derived from the COOP data.

To perform the temporal adjustment, monthly averages of the daily COOP values were corrected as follows:

For TMAX and TMIN:

$$Coop_{raw}(t) = Coop_{raw}(t) + (HCN(T) - Coop_{m}(T)) \qquad (1)$$

For PRCP:

$$Coop_{adj}(t) = Coop_{raw}(t) * (HCN(T) / Coop_{m}(T)) \qquad (2)$$

where $COOP_{adj}(t)$ is the adjusted daily COOP data value at time step t, $COOP_{raw}(t)$ is the unadjusted daily COOP data value at time t, $HCN(T)$ is the HCN/AHCCD monthly value at monthly time step T (the month within which t occurs), and $COOP_{m}(T)$ is the monthly averaged COOP value at time *T*. Note that a multiplicative approach is used in the case of precipitation to avoid introduction of negative precipitation values.

2.4. Topographic Adjustments to Temperature and Precipitation

Following Maurer *et al.* (2002) and Hamlet and Lettenmaier (2005), the temporally adjusted daily precipitation values were then rescaled by forcing the long-term mean values to match the monthly PRISM normals. The prior $1/8^{th}$ degree datasets used the 4km resolution PRISM normals based on the 1961-1990 climatology. The current data set instead uses the 30-arcsecond PRISM normals based on the 1971-2000 climatology (Daly et al. 2002). In Canada, only a 4km PRISM product reporting means for the 1961-2000 period was available. A quasi-30-arcsecond product for the 1971-2000 normals was developed by first estimating the 1971-2000 means from the available 1961-1990 product (via regression equations), and then interpolating from the 4km product to the 30-arcsecond resolution using an inverse square weighting with four nearest neighbors.

Additionally, a similar adjustment scheme was applied to daily maximum and minimum temperatures using the PRISM temperature normals. Temperature lapse rates vary strongly throughout the region and on daily time scales, and the typical approach of applying a constant standard atmospheric lapse rate of 6.1°C/km may cause a substantial temperature bias at higher elevations as well as introduce seasonal biases.

Topographic adjustment of precipitation on a monthly time scale is relatively straightforward: the ratio of monthly observed precipitation to monthly PRISM normals is calculated for each calendar month in the full time series (1971-2000), and this ratio is applied as a scaling factor to the entire daily time series. With temperatures, however, care must be taken to avoid introducing bias in the daily mean or daily range by adjusting maximum and minimum temperatures separately. Several important model-derived environmental variables (such as incoming solar radiation) depend on the range of daily temperatures, therefore the adjustment scheme used here was designed to explicitly preserve the range during the topographic adjustment. The daily temperature range was explicitly preserved by averaging each of the monthly PRISM and monthly mean COOP *Tmax* and *Tmin* values, and adding the offset to the *Tmax/Tmin* average at each daily time-step.

PRISM rescaling for PRCP:

$$PRCP_{adj}(t) = PRCP_{raw}(t) * [PRISM(T) / PRCP_m(T)] \tag{3}$$

PRISM rescaling for TMAX and TMIN:

$$\begin{gathered} TMAX_{adj}(t) = TMAX_{obs}(t) + \\ \left[\left(TMAX_{PRISM}(T) + TMIN_{PRISM}(T)\right)/2 - \left(TMAX_m(T) + TMIN_m(T)\right)/2\right] \end{gathered} \tag{4}$$

$$\begin{gathered} TMIN_{adj}(t) = TMIN_{obs}(t) + \\ \left[\left(TMAX_{PRISM}(T) + TMIN_{PRISM}(T)\right)/2 - \left(TMAX_m(T) + TMIN_m(T)\right)/2\right] \end{gathered} \tag{5}$$

where $TMAX_{obs}(t)$ and $TMIN_{obs}(t)$ are the temporally adjusted TMAX and TMIN values at daily time step t, $TMAX_{PRISM}(T)$ and $TMIN_{PRISM}(T)$ are the PRISM TMAX and TMIN values for monthly time step T (the month within which t occurs), and $TMAX_m(T)$ and $TMIN_m(T)$ are the monthly averaged (and temporally adjusted) TMAX and TMIN values for month T.

An additional corrective step was performed at this stage. For time steps where TMIN is greater than TMAX due to interpolation errors in the initial regridding step, the pseudo-mean of the inverted TMAX and TMIN values is offset by the difference in monthly PRISM and observed pseudo-means, and then a climatological daily range (from PRISM TMAX and TMIN) is applied:

$$\begin{gathered} TMAX_{adj}(t) = \left[\left(TMAX_{obs}(t) + TMIN_{obs}(t)\right)/2\right] + \\ \left[\left(TMAX_{PRISM}(T) + TMIN_{PRISM}(T)\right)/2 - \left(TMAX_m(T) + TMIN_m(T)\right)/2\right] + \\ \left[\left(TMAX_{PRISM}(T) - TMIN_{PRISM}(T)\right)/2\right] \end{gathered} \tag{6}$$

$$
\begin{aligned}
TMIN_{adj}(t) = {} & \left[\left(TMAX_{obs}(t) + TMIN_{obs}(t)\right)/2\right] + \\
& \left[\left(TMAX_{PRISM}(T) + TMIN_{PRISM}(T)\right)/2 - \left(TMAX_{m}(T) + TMIN_{m}(T)\right)/2\right] - \\
& \left[\left(TMAX_{PRISM}(T) - TMIN_{PRISM}(T)\right)/2\right]
\end{aligned}
\tag{7}
$$

Though this method cannot reconstruct the actual daily values, the climatological mean range is certainly preferred over the erroneous inverted values.

2.5. Wind data

Daily wind speed values for 1949-2006 were downscaled from National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis products (Kalanay *et al.*, 1996). For the years prior to 1949, a daily wind speed climatology (same value for each day of the year) was derived from the 1949-2006 reanalysis (Hamlet and Lettenmaier, 2005).

2.6. Description of final data set and applications

The final daily meteorological data set covers the period from Jan 1, 1915 to Dec 31, 2006 for the entire Columbia River basin and coastal drainages in the PNW. The data set is available on the study web site both as a daily and monthly summary product. The historical meteorological data set is an important input to the downscaling process described in Chapter 4 of this report. The downscaling process results in alternative daily meteorological data sets that reflect the changes in PNW climate simulated by specific global climate models. These data sets are the fundamental inputs to the hydrologic models described in Chapter 5 and 6 of this report that ultimately generate the hydrologic products described in Chapter 8. The meteorological driving data sets are also pre-processed by the hydrologic models to produce additional meteorological data for solar radiation at the surface, outgoing longwave radiation, dewpoint, relative humidity, and vapor pressure deficit. These supplementary data are available on the study web site.

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Statistical Downscaling Techniques for Global Climate Model Simulations of Temperature and Precipitation with Application to Water Resources Planning Studies

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1. Introduction

Downscaling is a term used to describe the process of relating information or data at relatively coarse spatial and temporal scales to desired products at finer spatial and temporal scales. In the case of climate impacts assessments, the process is commonly used to relate monthly simulations of temperature (T) and precipitation (P) data at approximately 200km resolution archived by a global climate model (GCM) to finer-scale information needed to drive a hydrologic model or other application model (e.g. daily data at 1/16th degree resolution needed to drive the VIC hydrologic model used in the studies described in this report—See Chapter X).

Downscaling approaches are generally designed to introduce fine-scale regional information, while preserving the most important and well-resolved climate signals that the models generate in response to greenhouse forcing. Because GCMs do not resolve the coastal mountains or smaller mountain ranges like the Cascades, east-west temperature and precipitation gradients in the Pacific Northwest are not appropriately simulated in the models, and attempts to use this data in its raw form will produce highly erroneous results. One can argue that large-scale features, such as north-south gradients along the west coast of the U.S., are better resolved because storm tracks in the cool season are related to large-scale storm systems that GCMs can resolve reasonably well (Salathé 2006). The position of the dominant storm track, however, can be strongly biased, and these biases can be different for different climate models, which creates difficulties when attempting to interpret changes at relatively small spatial scales (i.e. a particular river basin). Different climate models also show wide variations in their ability to accurately reproduce the key features of regional climate, and the quality of the time series behavior of different models also varies widely. Some models simulate a reasonably accurate ENSO cycle, for example, whereas others simulate this important driver of PNW climate relatively poorly. Some models may have too much interannual variability, others too little, etc.

GCM simulations of precipitation are much more problematic than those for temperature, and each GCM produces a unique sequence of decadal scale precipitation variability that makes comparisons between different GCM precipitation signals in a given future time frame problematic. This is particularly true in the PNW, where systematic changes in annual precipitation simulated by GCMs are relatively small, and decadal variability remains an important driver of future impacts in any given future decade (Mote and Salathé 2009). These considerations indicate the need for a multi-model ensemble approach to understanding regional climate changes.

Climate change studies to support water planning typically use GCM simulations to define scenarios of future changes in temperature and precipitation and related hydrologic variables such as snowpack, evaporation, or streamflow (Salathé et al. 2007). Approaches for downscaling GCM simulations can be broadly classified as "statistical" and "dynamical" downscaling techniques. Statistical downscaling methods are based on robust relationships between large-scale parameters that are well-resolved by a global model and observations at smaller spatial scales. In general, any number of large-scale fields may be used to predict a fine-scale parameter. For example, sea-level pressure and atmospheric moisture fields may be used to downscale regional precipitation. Dynamic downscaling techniques which employ regional climate models using relatively fine grid spacing (10-50km), to explicitly simulate fine-scale meteorological processes and feedback mechanisms. In particular regional climate models incorporate fine-scale topographic features (e.g. the Cascade mountain range in the PNW) that are not accounted for in GCM simulations (Salathé et al. 2007). There is currently great interest in dynamical downscaling techniques because they have the potential to explicitly simulate the spatial and temporal variability of changes in meteorological variables from first principles and to simulate local changes in temperature or precipitation that are potentially different from the climate signals from the global model (Salathé et al. 2009). These approaches, however, are still strongly limited by the computational requirements of the models used (which ultimately limits the number of realizations that can be produced). Furthermore, bias inherited from both the GCM simulation that drives the meso-scale model at the outer boundary combined with bias generated by the meso-scale models themselves can be substantial (Wood et al. 2004). Thus use of dynamic downscaling does not eliminate the need for statistical bias correction and downscaling. Given that dynamic downscaling approaches are still emerging as a practical resource for water planning, we will limit ourselves in this paper to a discussion of statistical downscaling approaches used in the studies described in this report. Salathé et al. (2007; 2009) provide an overview of dynamic downscaling approaches and the results for a recent case study for those interested in more details on this topic.

In this paper we will describe in detail two commonly used statistical downscaling approaches, develop a third approach which is a hybrid between the two methods, and discuss the strengths and limitations of each approach for various water planning applications. The paper is intended to provide a technical guide for water planning and management professionals who need to select a downscaling approach for particular water resources planning or assessment applications and is also intended to serve as a technical reference for the specific methods used for the Columbia Basin Climate Change Scenarios Project (CBCCSP) described in this report. The three downscaling approaches discussed in this chapter have been fully implemented in our study to provide meteorological inputs to the 1/16th degree VIC and 150m DHSVM hydrologic model implementations described in Chapter 5 and 6 of this report.

2. Downscaling Methodology

In this section, we first describe a process for selecting scenarios from the available GCMs, describe two statistical downscaling approaches that have been widely applied in previous water planning studies, and finally develop the methods for a third approach which is a hybrid between the two existing approaches, exploiting the relative strengths of each. For water planning studies, changes in daily minimum and maximum temperature (T) and precipitation (P) are the primary inputs needed to drive hydrologic models (See Chapter 5, 6), which in turn produce natural streamflow scenarios needed for various water resources applications. Following Widmann et al (2002), we use the GCM-simulated precipitation and temperature as the predictors for regional precipitation and temperature. While other parameters may improve downscaling skill in some regions, for the Pacific Northwest, the temporal variability of regional precipitation is well represented by large-scale precipitation simulations, which makes it a suitable predictor for statistical downscaling. Other variables needed for hydrologic simulation (such as humidity and solar radiation) are derived from T and P data in the hydrologic models used in this study (Maurer et al. 2002; Elsner et al. 2009, Chapter 5, 6).

2.1 Observed Meteorological Dataset

An observed meteorological data set implemented at 1/16th degree resolution has been implemented for the PNW (Chapter 3, this report). This data set serves as the basis for the GCM bias correction procedures (Section 2.4.1), and is also used to provide an observed daily time series which used in the two temporal disaggregation schemes described below.

2.2 Selecting Emissions Scenarios and Ranking GCM Performance

To provide inputs to the downscaling process, the first step is to select greenhouse gas emissions scenarios and a group of GCMs. GCM simulations are carried out by a number of independent research groups world wide, and take as inputs emissions scenarios generated for the Intergovernmental Panel on Climate Change (IPCC) assessment effort (SRES REF). The results of these modeling efforts are archived and distributed as the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. Although GCMs simulate a number of meteorological variables, we will confine our discussion to T and P which are the key inputs to hydrologic model applications.

2.2.1 Selecting Emissions Scenarios

Following the selection criteria developed by Mote and Salathé (2009), the IPCC “A1b” and “B1” emissions scenarios were selected for use in the study. A1b represents a medium emissions scenario associated with increasing greenhouse gases (and simulated PNW temperatures) through the end of the 21st century. The B1 scenario reflects significant greenhouse gas mitigation which begins to stabilize greenhouse gas concentrations (and simulated warming) by the end of the 21st century (Mote and Salathé 2009).

2.2.2 Evaluating and Ranking of Global Climate Models

The performance of global climate models may be evaluated using a variety of metrics depending on the qualities most important to a particular study. In general, the ranking will be depend on the metric used, and it is impossible to make an unqualified selection of the “best” climate models. Although skill in simulating the 20th century climate is one commonly used metric for evaluating GCMs, good performance for this metric does not guarantee that a model will give a realistic simulation of climate change associated with increasing greenhouse forcing (i.e. skill in reproducing historical variability and realistic greenhouse gas sensitivity are not necessarily related). For these reasons, the accepted approach to assessing climate change impacts is to use as large an ensemble of climate models as is computationally feasible. Model rankings, then, may be used to reduce the size of the ensemble by rejecting models that perform less well (*e.g.* Overland and Wang, 2007). For this study, we have used projections based on a selection of 10 global models whose 20th century simulations have the smallest bias in temperature and precipitation and that simulate the most realistic annual cycle in these parameters. These 10 models are sufficient to span the range of future climate change while reducing the computational demands of an even larger ensemble.

For particular applications, other qualities of the models may be important, such as the ability to simulate interannual variability associated with El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and other natural climate processes. A number of studies have addressed these issues, for example AchutaRao and Sperber (2006) for tropical ENSO, Overland and Wang (2007) for arctic climate variability, Brekke, *et al* (2008) for the State of California, and Reichler and Kim (2008) for global performance. Issues specific to the Pacific Northwest are addressed by Mote and Salathé (2009), including an analysis of North Pacific variability of temperature, precipitation, and sea-level pressures, which is a good indicator of skill in simulating ENSO and PDO teleconnections and other large-scale climate processes that influence the region. Here, we summarize model rankings for 20th century bias, a global performance index (AchutaRao and Sperber, 2006), and North Pacific variability (Mote and Salathé, 2009). Table 1 provides the ranking for the 10 models used in this report.

The five “best” models are shown in Table 2, based on the best combined rankings for Bias and North Pacific variability only. Note that incorporating the global metric (which is not available for ECHO-G) identifies the highest combined rank for four of the five models selected using only bias and North Pacific variability as the ranking criteria.

Table 1. Model ranking based on three metrics, 20th C bias, global climate patterns, North Pacific variability, and the sum of the Bias and North Pacific ranks. (A rank of 1 reflects the best performance, and a rank of 10 reflects the worst performance in the individual metrics.)

Model	Bias	Global	North Pacific	Sum All	Sum Bias and NP
UKMO-HadCM3	1	3	8	12	9
CNRM-CM3	2	7	4	13	6
ECHAM5/MPI-OM	3	2	3	8	6
ECHO-G	4	-	2	-	6
PCM	5	9	7	21	12
CGCM3.1(T47)	6	4	1	11	7
CCSM3	7	5	9	21	16
IPSL-CM4	8	8	10	26	18
MIROC3.2(medres)	9	6	5	20	14
UKMO-HadGEM1	10	1	6	17	16

Table 2. Five best models based on combined bias and North Pacific variability metrics in Table 1

Model	Bias	Global	North Pacific	Sum All	Sum Bias and NP
CNRM-CM3	2	7	4	13	6
ECHAM5/MPI-OM	3	2	3	8	6
ECHO-G	4	-	2	-	6

CGCM3.1(T47)	6	4	1	11	7
UKMO-HadCM3	1	3	8	12	9

2.3 Delta Method Downscaling Approaches

The so called “delta method” is conceptually very simple and has been widely applied in water planning studies, particularly in earlier studies (prior to about 2000) when GCM resolution was typically very coarse and the models were only capable of simulating regional-scale changes in T and P (e.g. Lettenmaier et al. 1999). Although some variations have been developed, a common application of the delta method will apply monthly changes in temperature and precipitation from a GCM, calculated at the regional scale, to an observed set of station or gridded temperature and precipitation records that are the inputs to a hydrologic model. The meteorological variables from the GCM simulation are typically averaged over an historic period from a control simulation and a future period from a scenario simulation to estimate the changes. Mote and Salathé (2009), for example, compared simulations from twenty GCMs, averaged over the entire PNW, for a 30-year window centered on the 1980s (1970-1999) to three future 30-year windows centered on the 2020s (2010-2039), 2040s (2030-2059), and 2080s (2070-2099). For this study, we use the gridded historical meteorological dataset described above. Changes in mean climate, calculated for each calendar month, are applied at daily time scale for each 1/16th degree grid cell, as follows:

For all grid cells in the domain:

$$P_{new} = P_{obs} * P_{fact} \quad (1)$$

Where P_{fact} is the ratio of the CGM simulated mean precipitation from the future time period relative to the historic period (1970-1999), averaged over the geographical region of interest, in this case, the states of Washington, Oregon, and Idaho.

$$T_{new} = T_{obs} + T_{delts} \quad (2)$$

Where T_{delta} is the difference in the CGM simulated mean temperature from the future time period relative to the historic period, averaged over the geographical region of interest.

Note that multiplicative perturbations are used for precipitation to avoid potential sign problems (i.e. the potential to calculate negative precipitation using an additive approach), and additive perturbations are used with T to avoid problems with T not being on an absolute scale (i.e. the centigrade scale is zero at the freezing point of water at standard pressure, not at absolute zero).

To give an example, suppose an analysis of a particular GCM simulation showed 2 C warming in January for a future 30-year window, with an increase in P of 10%. In this case $T_{delta} = 2.0$, and $P_{fact} = 1.1$. These perturbations are applied uniformly over the entire domain at a daily time scale to the full timeseries of observations. Thus daily gridded observations of T and P are forced to reproduce a region-wide change in the long-term mean for each month estimated from the raw GCM data. Many features of the original time series and spatial variability of the gridded observations are preserved by the delta method, and any bias in the mean in the GCM simulations is automatically removed during the process. Changes in the seasonality of temperature and precipitation are captured, but the climate change perturbation is the same at all points in the region. The only fine-scale information (spatial or temporal) comes from the observed dataset.

2.3.1 Advantages and Limitations of the Delta Method

A key advantage of the delta method is that observed patterns of temporal and spatial variability from the gridded observations are preserved, and comparison between future scenarios and observations is straight-forward and easily interpreted. The time sequence of events matches the historic record in the gridded data sets, facilitating direct comparison between the observations and future scenarios. For example, particular drought years in the historic record can be directly compared in the historic and future simulations. Bias from the GCMs is not introduced, and the spatial resolution of the

GCM (which is different for different GCMs) is not very important given that the changes are calculated at the regional scale. Thus the delta method facilitates a direct comparison of different GCMs with different error characteristics, different patterns of spatial and temporal variability, etc. In the PNW, which is strongly affected by the El Nino Southern Oscillation (ENSO), the ability of a particular GCM to simulate the variability of tropical sea surface temperatures (and the large-scale teleconnections to the PNW associated with these variations) is an important element of the time series behavior of the scenario. By discarding the temporal information from the GCM and forcing the behavior of T and P in the future scenario to match observed patterns associated with ENSO, the delta method facilitates the comparison of changes in T and P from GCMs with potentially very different performance in this regard.

The strengths of the delta method are also its key limitation, because, by design, no information about possibly altered temporal or spatial information is extracted from the GCM simulations. So, for example, while some monthly information about the regional-scale intensity of climatic extremes from the GCM simulation is captured by the delta method, no information from the GCM about potentially changing *interarrival time, duration, or spatial extent* of climatic extremes (e.g. droughts and floods) is captured by the delta method. Likewise, only changes in monthly means are captured, and other potential changes in the probability distributions of T and P are ignored. Thus a key limitation of the delta method is that potential changes in the variability or time series behavior of T and P are not captured by the approach.

2.4 Bias Correction and Statistical Downscaling

The statistical downscaling technique that has come to be called Bias Correction and Statistical Downscaling (BCSD) was first developed in seasonal to interannual forecasting applications (Wood et al. 2002) and has been widely applied in monthly time scale climate change studies in the West in recent years (e.g. Payne et al. 2004;

Kristiansen et al. 2004; Van Rheenen et al. 2004; Vicuna et al. 2007). The approach is carried out in three essentially distinct steps:

1. Statistical bias correction of GCM simulations of T and P at the GCM grid scale and monthly time step,
2. Spatial downscaling from the GCM grid to the grid scale of interest (in our case 1/16th degree),
3. Temporal disaggregation from monthly to daily time scales

We describe each of these steps below.

2.4.1 Statistical Bias Correction

Statistical bias correction is carried out by first aggregating the gridded T and P observations to the GCM grid scale (typically about 200km resolution), and then using quantile mapping techniques to remove the systematic bias in the GCM simulations (Wood et al. 2002). Quantile mapping techniques work by creating a one-to-one mapping between two cumulative distribution functions (CDFs): one based on the GCM simulations and the second based on the aggregated observations. The mapping process is based on a simple nonparametric lookup procedure (Figure 1). If the GCM simulation of T or P for a particular month represents the estimated Xth quantile in the cumulative distribution function for the GCM simulations over a certain period, then the Xth quantile is looked up in the cumulative distribution function for the aggregated T or P observations for the same period, and this new value becomes the "bias corrected" GCM value for that month (Figure 1). After applying this procedure, by construction, the bias corrected GCM simulations have the same CDF as the aggregated observations for the training period used to construct the two CDFs. It should be noted that no assumptions about the nature of the two probability distributions is required, and the process fully preserves the nature of the extremes in the observed CDF. For this study, the mapping between GCM values and aggregated observed values is based on a 1950-1999 training period. The bias in the model is assumed to be constant and to extend to future simulations as well. (This assumption is well supported by the experiments carried out by Salathé (2004) who showed, using split sample tests of 20th century climate records, that the bias correction process performed equally well when trained on Pacific Decadal Oscillation (PDO) warm phase epochs and validated on cool phase PDO epochs, as when trained on cool phase epochs and validated on warm phase epochs.) The CDF is allowed to evolve in the bias-adjusted future projection (in response to the systematic changes in the raw simulations), but with the bias relative to the observed climate removed. The output of this process is a bias corrected version of the large-scale GCM monthly time series for T and P for the entire GCM monthly time series (in our case from 1950-2099).

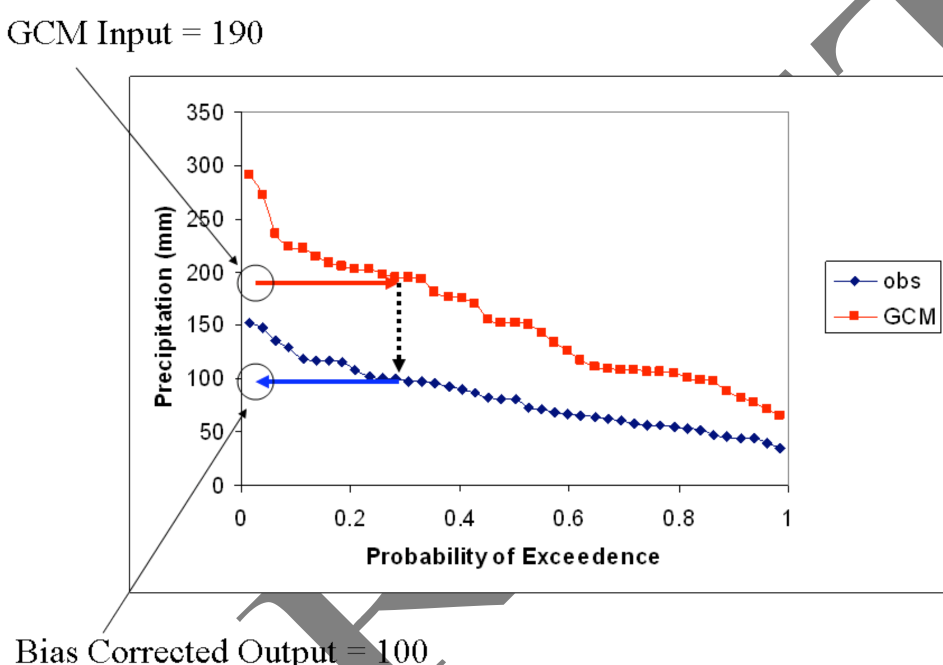

Figure 1. Schematic diagram showing the quantile mapping process used for GCM bias correction.

2.4.2 Spatial Downscaling

After large-scale bias correction, the monthly T and P values at the GCM grid scale are interpolated to the fine scale grid (1/16th degree). Our version of this approach uses an inverse square weighting using four nearest neighbors. These values are then scaled to produce the fine-scale spatial variability of the gridded observations. For precipitation, a multiplicative factor is applied, and, for temperature, an additive factor is applied. The factors are computed for each calendar month as the ratio or difference between the GCM and observed values for the period 1970-1999. Thus the bias-corrected, large-scale anomalies are used to estimate a time series of monthly values at the fine grid scale.   Note that anomalies based on 1970-1999 are used in this step to establish a common baseline with the traditional delta method approaches described above.

2.4.3 Temporal Disaggregation

Finally, the monthly time series at each grid cell is temporally disaggregated to daily time scale by a random sampling of observed daily variability represented by a carefully screened set of relatively wet months. The choice of relatively wet conditions as the basis of the basis of the temporal downscaling step is intended to minimize the occurrence of a relatively wet month being paired to a relatively dry daily time series at the grid scale, which can create unrealistically large daily precipitation values.   In the most recent version of the code that we use here, an arbitrary ceiling of 150% of the observed maximum precipitation value for each cell is also imposed by “spreading out” very large daily precipitation values into one or more adjacent days. The value of precipitation for the month is preserved, however.

2.4.4 Advantages and Limitations of the BCSD Method

The BCSD approach is conceptually attractive in comparison with the relatively simple delta method because it extracts more information from the GCM simulations. The transient time series behavior of the monthly GCM simulations, although bias corrected, is largely preserved by the downscaling, and the large-scale spatial variability of the GCM simulations of T and P is also incorporated in the final results. Although the daily patterns within the month are extracted from observations, the changes in precipitation and temperature extremes are potentially very different in comparison with delta method approaches that only perturb the mean monthly value on a regional basis. The use of the BCSD for multiple GCMs facilitates a very straight-forward approach to estimating the uncertainty of outcomes in any future time period using ensemble methods. BCSD downscaled transient runs also contain realizations of interannual and interdecadal variability that may be different from those in the historic record. As noted above, the BCSD approach has been widely applied in a number of large-scale, monthly water planning studies (e.g. Payne et al. 2004; Christensen et al. 2004), and at these spatial and temporal scales the approach has worked reasonably well.

As for the delta method approach, the source of the strengths of the BCSD method is also the source of its limitations. Incorporating more information from the GCM simulations is not necessarily valuable if the information is of poor quality, and in the context of an ensemble analysis, the results may be difficult to interpret if the quality of information varies substantially from GCM to GCM. Extracting a time series directly from the GCM provides an explicit transient realization that is potentially valuable, however, as discussed in Section 2.1 many GCMs do not accurately simulate interannual climate variability in the PNW, which raises concerns about the accuracy of the future time series as well. Another limitation is that the climate change signal in temperature and precipitation relies only on information represented in the global model. As noted in the introduction, the spatial patterns in GCM data (particularly east-west gradients) are not reliable since the terrain features that determine spatial variability in the climate are not represented in the global models. Widmann et al. (2002) introduced an approach intended to improve the downscaling of terrain effects by considering both the large-scale precipitation and circulation patterns from the GCM simulations (Salathe et al. 2004).

Finally, due to the disaggregation of monthly data, daily time step realizations from BCSD downscaling have been found to frequently contain unrealistic daily precipitation estimates, especially at smaller spatial scales of interest in water resources planning. These artifacts of the downscaling approach can occur, for example, when a relatively wet future condition is paired at specific grid locations with a relatively dry month used for daily disaggregation. In effect a few isolated storms in the dry month are made much larger to reflect the relatively wet month from the GCM simulation. Although the version of the BCSD code used in this study places some quantitative (but essentially arbitrary) limits on increases in daily precipitation during the temporal disaggregation step (see Section 2.3.3), the effects on daily precipitation must be interpreted with caution. We should note that these daily time step artifacts are not at all related to GCM signals, which are incorporated only at monthly time scales (Maurer and Hidalgo 2008).

Thus current versions of the BCSD downscaling approach are probably best applied to GCM simulations which simulate the monthly time series behavior of the historic period for the region in question relatively accurately. Use of these results is also best confined to monthly analysis at moderate to large spatial scales because of downscaling artifacts which can produce questionable daily precipitation estimates, particularly at smaller spatial scales. Use of the BCSD approach for daily flood risk analysis, for example, would probably not be a good choice, both because the size of storms is not necessarily realistic, and precipitation extremes can be exaggerated as discussed above.

2.5 Hybrid Delta Approach

As discussed in the introduction, the hybrid delta (HD) downscaling technique is a new approach developed specifically for the CBCCSP to support applications that require realistic daily time step information at relatively small spatial scales. It combines some of the best features of the traditional delta method and BCSD approaches discussed above, while avoiding many of the limitations of each. In particular, the method preserves the time series behavior and spatial correlations from the gridded T and P observations (a key advantage of the traditional delta method), but transforms the entire probability distribution of the observations at monthly time scales based on the bias corrected GCM simulations (a key advantage of the BCSD method).

The approach begins by applying the BCSD approach to produce a monthly time series of T and P, downscaled to the fine-scale grid ($1/16^{th}$ degree in our case) as described in Section 2.3.1 and 2.3.2 above. Monthly data for a future 30-year window at each grid cell location are segregated into individual calendar months (i.e. all the Januarys, Februarys, etc.) and these data are then ranked from highest to lowest value. An unbiased quantile estimator is used to assign a plotting position to the data for each calendar month based on the Cunnane formulation (Stedinger et al. 1993):

$$q = (i - 0.4)/(n + 0.2) \qquad (3)$$

where q is the estimated quantile (or probability of exceedance) for the data value of rank position i (rank position 1 is the highest value), for a total sample size of n. Historic T and P observations are processed in the same manner for each calendar month and grid cell.

The final steps in the HD downscaling approach use the same quantile mapping approaches discussed in Section 2.3.1, but the technique is inverted in this case to achieve a different objective. Instead of bias correcting a GCM simulation to match observations, the observations are re-mapped onto the bias corrected GCM data to produce a set of transformed observations reflecting the future conditions. Figure X shows a schematic of the final steps in the data processing sequence. The process is probably best described by giving an example. For each individual grid cell, a T or P value from the observed monthly time series is mapped from the observed quantile position for that calendar month to the corresponding quantile from the bias corrected GCM data associated with a future scenario. I.e. if October, 1916 from the observed time series is the 87th percentile of all the Octobers in the observed time series, this monthly value is mapped to the 87th percentile of all the bias corrected GCM Octobers for the future scenario. To produce a daily time series, the daily values within the observed month are then rescaled so that they reproduce the new monthly value. The entire observed time series of T and P at each grid cell is perturbed in this manner using the observed and GCM distributions for each calendar month, resulting in a new time series that has the statistics of the bias corrected GCM data for the future period, but essentially preserves the time series and spatial characteristics of the gridded T and P observations.

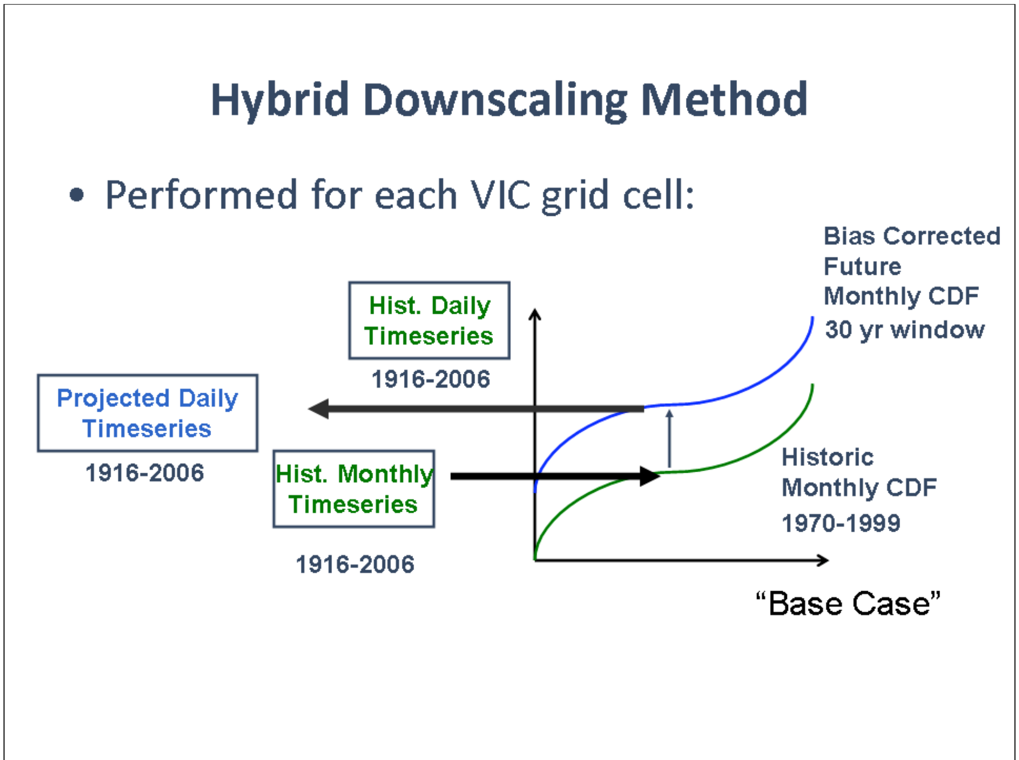

Figure 2 Schematic diagram of the final data processing steps for the hybrid delta downscaling method.

Simulated values that are outside the observed quantile map (which can occur because we use a relatively short window from 1970-1999) are interpolated using standard anomalies (i.e. standard deviations from the mean). Although this approach ostensibly assumes a normal distribution, it was found during testing to be much more stable than more sophisticated approaches. In particular, the use of Extreme Value Type I (EV1) distributions for extending the tail of the probability distributions was found to be highly unstable in practice and introduced large errors in daily extremes in many grid cells.

The key difference between the hybrid delta approach and the traditional delta method is that the entire probability distribution at monthly time scale is adjusted to reflect the GCM data. Thus changes in the mean, variance, skewness or other statistical features of the GCM data are reproduced explicitly in the future scenarios. Unlike the BCSD approach, however, which can produce highly unrealistic daily time series behavior (particularly for P), the approach maintains realistic values by closely aligning the time series and spatial behavior of the future values with the gridded observations. In particular, the random pairing of wet future months with dry observed months that frequently produces unrealistic daily precipitation values in the BCSD approach is completely avoided. The HD method also provides a static 91-year climate time series representing a 30-year future time horizon. This has an advantage in comparison with the BCSD method in allowing better representation of statistical parameters such as return periods of climatic or hydrologic extremes that are of interest to water resources planners.

3. Comparison of Three Downscaling Methods

To illustrate some of the key differences between the different downscaling approaches described above, in this section we show the spatial distribution of temperature and precipitation changes for January over the PNW for a single GCM, simulated natural streamflow for a moderate sized basin on the east side of the Cascades (The Yakima River at Parker USGS 12505000), and simulated flood risk for the Kettle River at Westbridge (Environment Canada 08NN003) in British Columbia.

Figure 3 shows the spatial variability of average changes in January precipitation and average temperature over the PNW. Note that the traditional delta method approach would show a constant change over the entire domain, whereas the BCSD and hybrid delta maps show considerable spatial variability. For the Yakima River basin (outlined in Figure 3), for example, temperatures are much warmer than for the region as a whole, and the northern portions of the Columbia basin show much larger increases in precipitation than other parts of the domain. The spatial variation in temperature in the BCSD and hybrid delta runs has a substantial influence on the loss of snowpack (and resulting streamflow timing shifts) in the hydrologic simulations (Figure 4). Similarly estimates of flood risk for the Kettle River (Figure 5) are markedly different for the ensemble of hybrid delta method simulations (which shows little systematic change in flood risk) in comparison with the traditional delta method approach (which shows strong declines in flood risk). These differences are related to the spatial distribution of precipitation changes incorporated in the hybrid delta approach.

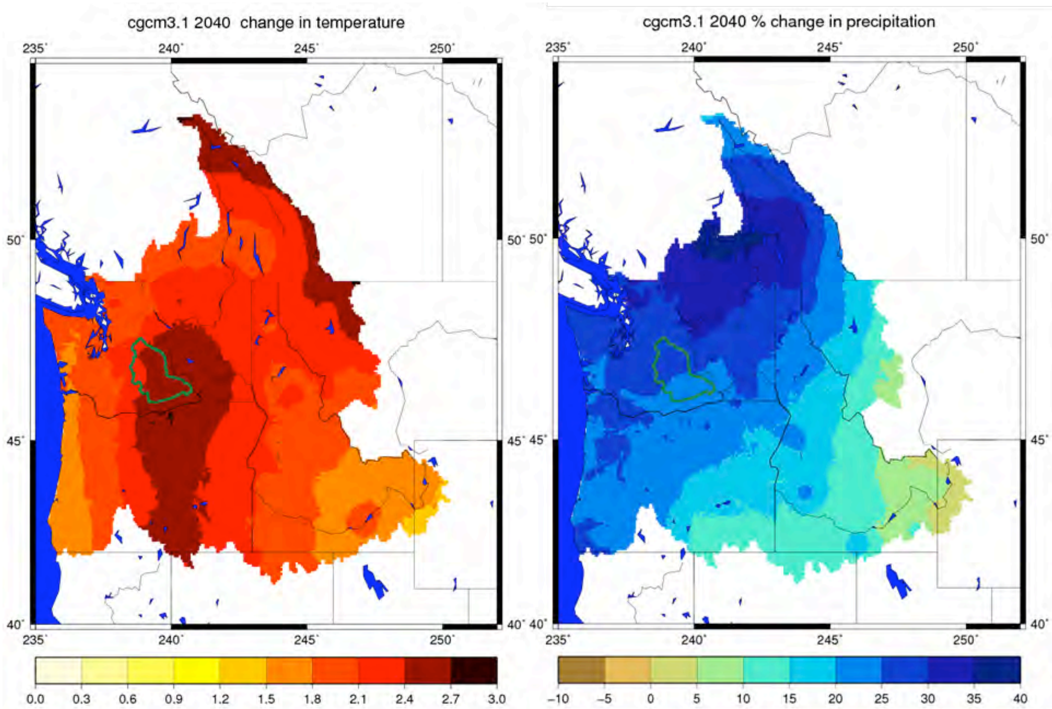

Figure 3. Spatial plots of changes in January average temperature (left, in˚C) and precipitation (right, in %) for the 2040s for the CGCM3 (T47) GCM and A1b emissions scenario. The outline of the Yakima River basin upstream of USGS 12305000 (Yakima River at Parker) is shown.

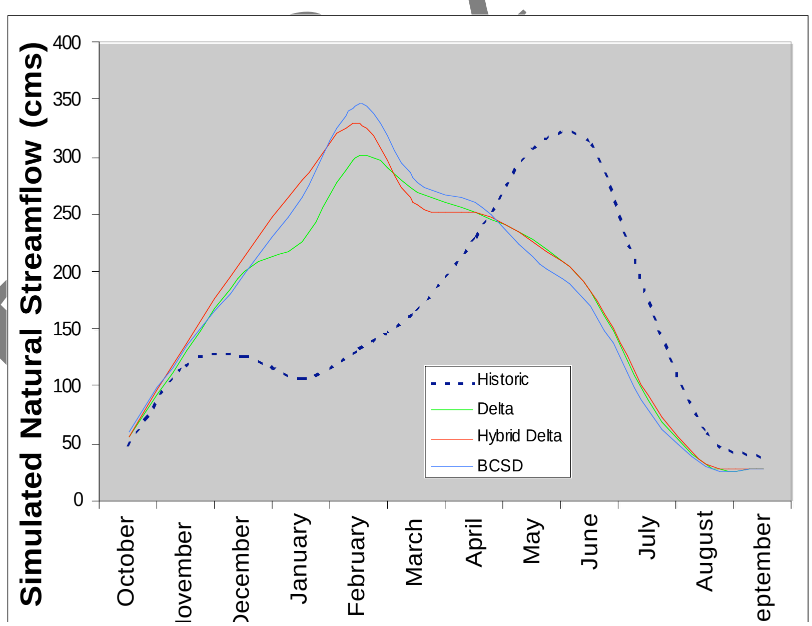

Figure 4 Long-term mean simulated monthly hydrograph for the Yakima River at Parker (USGS 12505000) for historical condition and three different downscaling approaches applied to the 2040s A1b CGCM3 (T47) GCM scenario. Historic, delta, and hybrid delta averages are

calculated from the 30-year window associated with "1970-1999", BCSD values are averaged from the 30-year window from 2030-2059 in the transient simulation.

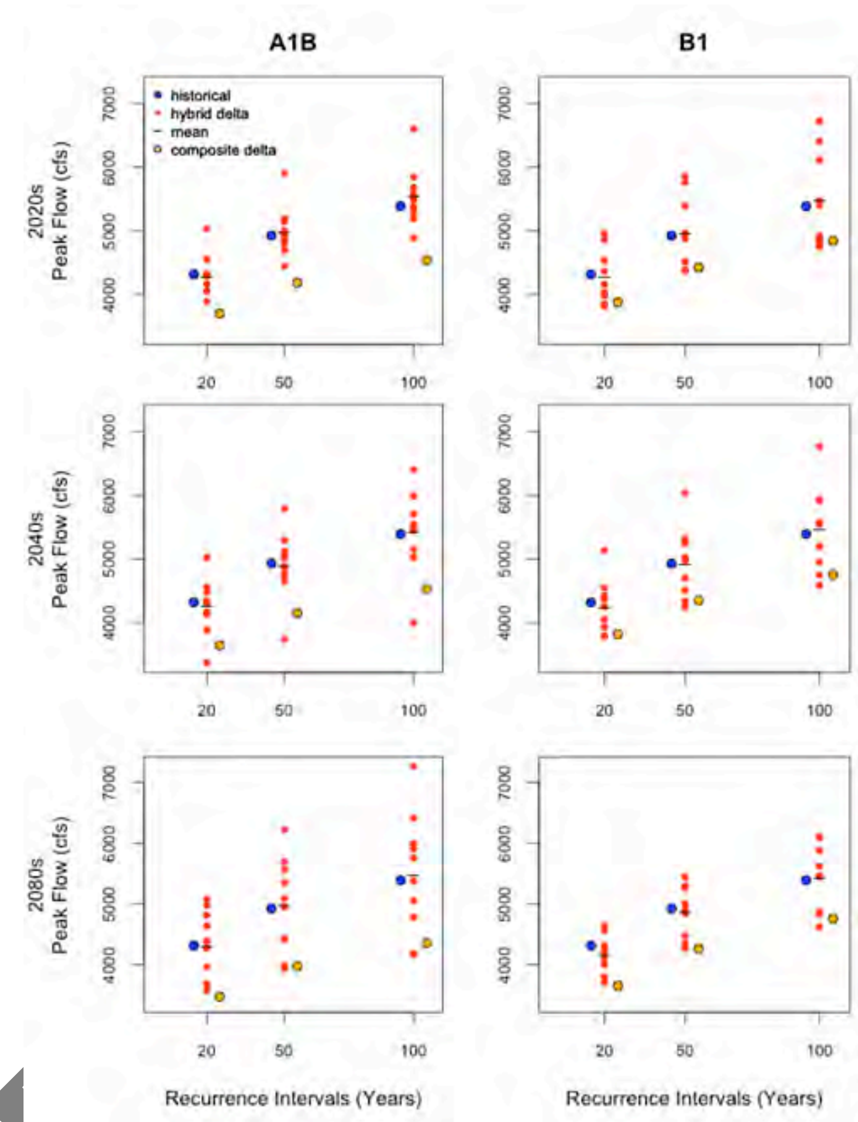

Figure 5 Estimates of flood risk at the 20, 50, and 100 year recurrence interval for the Kettle River at Westbridge (Environment Canada 08NN003). The figures show flood risk for historical simulations (single blue dot), an ensemble of 10 hybrid delta scenarios (range of red dots), and the associated delta method scenario (yellow dot), respectively.

4. Guide to Applications

In this section we discuss choice of downscaling technique for particular water planning applications. Table 1 summarizes a number of key features of the three statistical downscaling approaches outlined in Section 2.

Table 1: Key Features of the Different Downscaling Approaches

Feature	**Delta Method**	**BCDC**	**Hybrid Delta**
Source of interannual and interdecadal climate variability	Observations	GCM	Observations
Source of interarrival time and duration of droughts and floods	Observations	GCM	Observations
Source of spatial variability	Observations	Observations/GCM	Observations/GCM
Captures change in mean T and P mean from climate model?	Yes	Yes	Yes
Captures change in variance of T and P from climate model?	No	Yes	Yes
Captures change in monthly T and P extremes?	No	Yes	Yes
Captures change in daily T and P extremes?	Yes, but only via changes in monthly means	Yes, but only via changes in monthly statistics	Yes, but only via changes in monthly statistics
Future monthly T and P statistics directly comparable with observations?	Yes	Yes (but not necessarily at relatively small spatial scales)	Yes
Future daily T and P statistics directly comparable with observations?	Yes	No	Yes

4.1 Applications of the Delta Method

The delta method is often applied in the context of an easily interpreted sensitivity analysis, or when a few model runs are intended to capture the consensus of a suite of T and P changes from a group of climate model simulations. In applications where the time series behavior of T and P is a key driver of outcomes (e.g. in the case of estimating drought statistics) and is not necessarily simulated well (or equally well) for different GCMs, the choice of the delta method may avoid these difficulties. In applications where a large number of realizations of variability for a consistent level of systematic change is desirable (e.g. for testing a water supply system for reliability), the delta method provides a very straight-forward framework for the analysis. Delta method experiments are also a good framework for sensitivity analysis of changes in flood and low flow risks associated with systematic warming and changes in mean monthly precipitation statistics (see for example Mantua et al. 2009).

4.1.1 Delta Method Runs for the Columbia Basin Climate Change Scenarios Project

For the PNW, we currently have 91 years of observed climate (1916-2006), to which a number of delta method perturbations can be applied. This can be accomplished either in an ensemble mode (i.e. one run per individual GCM), or in a consensus mode (i.e. average changes in T and P from all GCMs encompassed in a single run). For this study, we have chosen to focus on the latter approach and provide six traditional delta method runs, representing the consensus of changes in T and P for the 10 best climate models (discussed above) for three future time periods and two emissions scenarios. These are also essentially the same six scenarios that formed the core of the Washington Climate Change Impacts Assessment (Elsner et al. 2009).

4.2 Applications of the BCSD Approach

One of the key advantages of the BCSD approach is that it provides a transient realization that explicitly reproduces the monthly time series behavior of the GCM T and P simulations, in our case from mid-20th century to the end of the 21st century. Thus for analyses that are potentially sensitive to changing time series behavior, the BCSD may provide useful information that is missing from the delta method or HD runs. For example, potentially changing drought interarrival and duration statistics would probably be best analyzed using a BCSD approach, because the time series behavior of T and P is a key determinant of these statistics. Likewise, any analysis that is focused on rates of change through time is well served by the BCSD approach. For example, trends in the date of peak snow water equivalent or the centroid of timing of streamflow can only be examined in the context of a transient run.

Another advantage of the BCSD approach is that any future time period can be analyzed, as compared to delta method and HD runs which impose changes from a fixed 30-year future period on a long historic record of observed variability. So, for example, an analysis of the 30-year period centered on the 2060s is easily extracted from a BCSD transient run without making new hydrologic model runs.

Since daily time step data are generated by a non-physical disaggregation of monthly-mean climate model output, considerable caution should be exercised in using daily results associated with BCSD approaches, and in general the analysis should be confined to bi-weekly or monthly analysis at medium to large spatial scales. So, for example, analysis of flood risk (which is strongly influenced by daily precipitation statistics) would not, in general, be a good application for BCSD approaches, particularly at smaller spatial scales. Basinwide hydropower studies in the Columbia River basin at monthly time step, however, would probably be well served by the BCSD approach (see e.g. Payne et al. 2004)

4.2.1 BCSD Runs for the Columbia Basin Climate Change Scenarios Project

For the current study, we provide 10 BCSD runs associated with the 5 best GCMs (see Section 2.1) and two emissions scenarios (A1b and B1). This choice of only the five best GCMs for analysis reflects the fact that, without reasonable reproduction of historic climate variability by the GCM, it is hard to argue that explicitly incorporating this information in the downscaling is valuable. Furthermore A1b and B1 results are not dramatically different until late in the 21st century, so a total of 10 runs over the two scenarios provides enough sample size for a reasonably detailed analysis of model uncertainty for the different GCMs for the 2020s and 2040s. For the 2080s the spread of results are dominated by emissions uncertainties rather than modeling sensitivity (Mote and Salathé 2009), so having a relatively small sample of GCMs is probably less important.

4.3 Applications of the Hybrid Delta Approach

Because the HD approach incorporates the strengths (and avoids most of the limitations) of both delta method and BCSD approaches, we are recommending that this approach be used as the primary product for most kinds of water resources analyses. The HD approach is suitable for water resources planning at both daily and longer time scales, supports analysis of daily hydrologic extremes such as flood and low flow risk, and provides consistency across a range of spatial scales that is comparable to that produced by hydrologic model simulations using observed T and P data. In particular, results at smaller spatial scales are less likely to be affected by daily time step disaggregation artifacts that are commonly encountered in products produced using the BCSD approach. Although duration and interarrival time of droughts are essentially those of the historic record in the HD products, the effects of changing drought intensity associated with changing probability distributions of monthly T and P statistics can be analyzed using the HD approach at daily time scales. Furthermore, without daily time step data from the global models, there is not a secure basis for projecting changes in the daily statistics of T and P under climate change. Indeed, such changes are best studied using high-resolution regional climate models that can simulate the physical processes that control such changes (Salathé et al. 2009).

4.3.1 Hybrid Delta Runs for the Columbia Basin Study

Sixty future Hybrid Delta runs will be produced for the CBCCSP based on the ten best GCMs, three future time periods, and two emissions scenarios. This strategy will produce a relatively large sample size to support a detailed uncertainty analysis of key hydrologic variables for each future time period.

5. Conclusions

A number of different statistical downscaling approaches have been developed to provide gridded T and P data at local-scales derived from large-scale, monthly GCM simulations of T and P. Both the traditional Delta Method, and widely used BCSD approach have different strengths and limitations, and are most suitable for different kinds of applications. The Hybrid Delta method developed in this study combines the key strengths of each approach, while largely avoiding the limitations of each. Although a few specific applications can only be addressed using the transient products produced by the BCSD approach, the Hybrid Delta approach can be used successfully in most water resources applications. For this reason we have chosen to use the Hybrid Delta method as the corner stone of the hydrologic analysis in the CBCCP.

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MACRO-SCALE HYDROLOGIC MODEL IMPLEMENTATION

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1. Introduction

In recent years the impacts of climate change on water resources in the Pacific Northwest (PNW) has been widely recognized (Chapter 1, this report). Approaches that couple downscaled climate scenarios (Chapter 2, this report) to a physically based hydrologic model have provided an effective means of assessing the impacts of global climate change on hydrology (e.g. Elsner et al. 2009), water resources systems (e.g. Hamlet et al. 2009; Vano et al. 2009), and the natural environment (e.g. Littell et al. 2009). In these studies the hydrologic model functions as a "translator" between changes in climate and hydrologic changes such as loss of snowpack, altered streamflow timing, changing evaporation, etc.

The Variable Infiltration Capacity (VIC) macro-scale hydrologic model used in this study has been used to assess the impact of climate change on hydrology of the Columbia River (CRB) basin in a number of previous studies. The Intergovernmental Panel on Climate Change (IPCC) produces an assessment of the state of climate change science approximately every 7 years and as part of the assessment, climate change scenarios from global climate models (GCMs) are published for use by researchers to conduct their own regional assessments. Hamlet and Lettenmaier (1999) studied the implications of GCM projections from the second IPCC assessment (1995) over the Columbia River Basin. Following the third IPCC Assessment Report (2001), Payne et al. (2004) studied climate change effects on the Columbia River Basin. Lee et al. (2009) explored the effects of projected hydrologic change on flood control operations. All of the above studies employed VIC implementations at 1/8th degree (latitude longitude) resolution.

Such studies have succeeded in providing useful climate change scenarios for large-scale planning in the basin, but have limited ability to accurately resolve smaller sub-basins of interest to other stakeholders (Chapter 1, 2, 8). To better resolve smaller watersheds, we have implemented the VIC hydrologic model at 1/16th degree latitude by longitude resolution across the CRB (approximately 30km^2 or 7400 acres per cell), extending the VIC model developed for the Washington State Climate Change Impacts Assessment (Elsner et al. 2009). In addition to the macro-scale VIC implementation, a fine-scale hydrologic implementation using the Distributed Hydrology Soil Vegetation Model (DHSVM) has been carried out at 150m resolution over 5 pilot watersheds that cover a range of terrain and climatic conditions within the CRB (Chapter 6).

This chapter describes the macro-scale VIC model, implementation and model calibration procedures, and evaluation of the macro-scale hydrologic scenarios which form the basis for the core hydrologic data bases produced for this study (see Chapter 8, this report). The fine scale hydrologic model implementation is described in Chapter 6 (this report).

2. Approach/Methods

The methods outlined in this section incorporate a number of important improvements in the macro scale hydrologic model and its implementation. The most important of these changes is the increased spatial resolution of the VIC hydrologic model and recalibration of this model over the entire CRB. Important changes in the downscaling procedures used to translate GCM simulations to driving data for the hydrologic models have also been made (See Chapter 4 on GCM Downscaling Methods and Applications). An historical input data set including daily precipitation, maximum and minimum daily temperature, and windspeed was developed for this study at 1/16th degree spatial resolution and its unique features are described in Chapter 3 on historic meteorological driving data.

The comprehensive hydrologic databases produced for the entire CRB (Chapter 8) are based upon simulations using the VIC macro-scale hydrologic model (Liang et al. 1994; Liang et al. 1996; Nijssen et al. 1997) implemented at 1/16th degree resolution. This implementation allows for a more accurate rendering of topographic features and the sensitivity of smaller watersheds to changes in climate forcing. The current VIC implementation extends the 1/16th degree VIC implementation developed for the WACCIA (Elsner et al. 2009). While Elsner et al. (2009) primarily used model parameters calibrated at the 1/8th degree scale and applied them at 1/16th degree, here we follow the approach of Matheussen et al. 2000 to calibrate 12 large watersheds in the CRB at the 1/16th degree scale (see Figure 1). Further model evaluation at smaller watershed scales has been conducted for streamflow locations for which naturalized flow data was available. Further details of the calibration approach are provided in Section 1.5. Further details of the statistical bias correction approach are provided in Chapter 8 on data products.

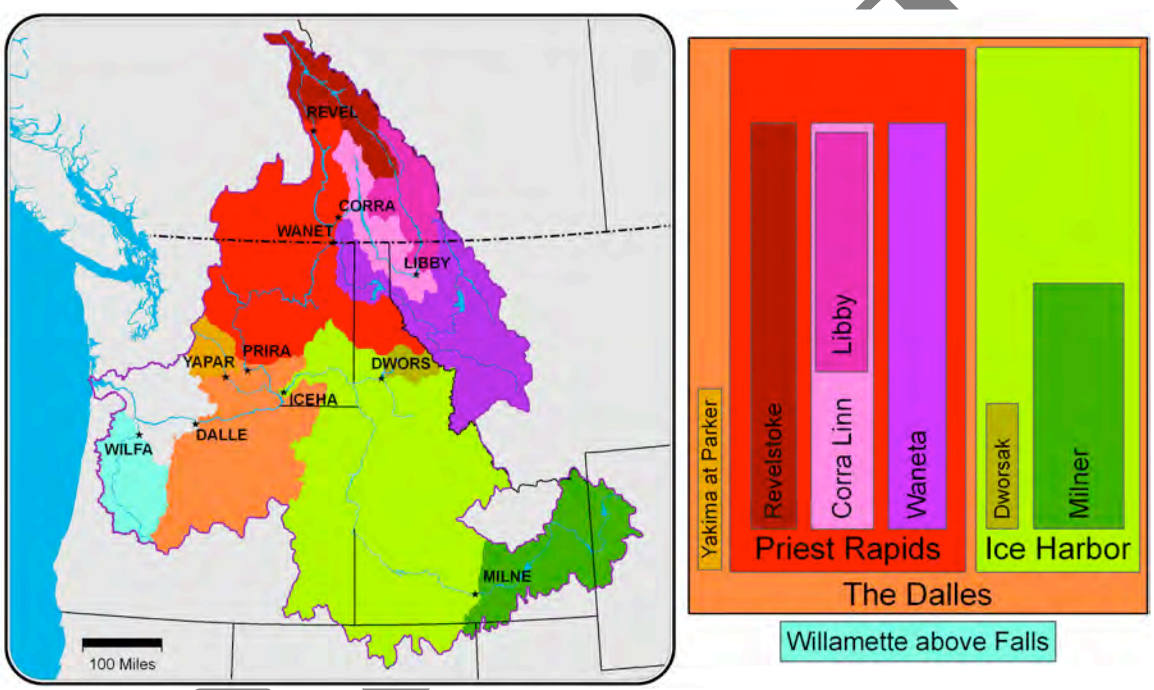


Figure 1 Overview map of Columbia River watershed and coastal drainages to Washington and Oregon.

2.1 Overview of the Variable Infiltration Capacity Model

The VIC model (Liang et al. 1994; Liang et al. 1996; Nijssen et al. 1997) is a spatially distributed hydrologic model that solves the water balance at each model grid cell (see Figure 2 for diagram). Its initial purpose was to serve as a land surface model incorporated dynamically in a global climate model which would more accurately simulate land processes that a GCM cannot explicitly resolve. For off line studies (i.e. when not incorporated in a climate model) the model can also be run in “water balance” mode, in which case the surface temperature is assumed to be equal to the air temperature. This approach reduces computational requirements, and has been frequently used for water resources studies like this one. At 1/16th degree resolution, the VIC model is most appropriately applied at spatial resolutions of about 500km^2 or greater (193 mi^2), which equals approximately 15 model grid cells.

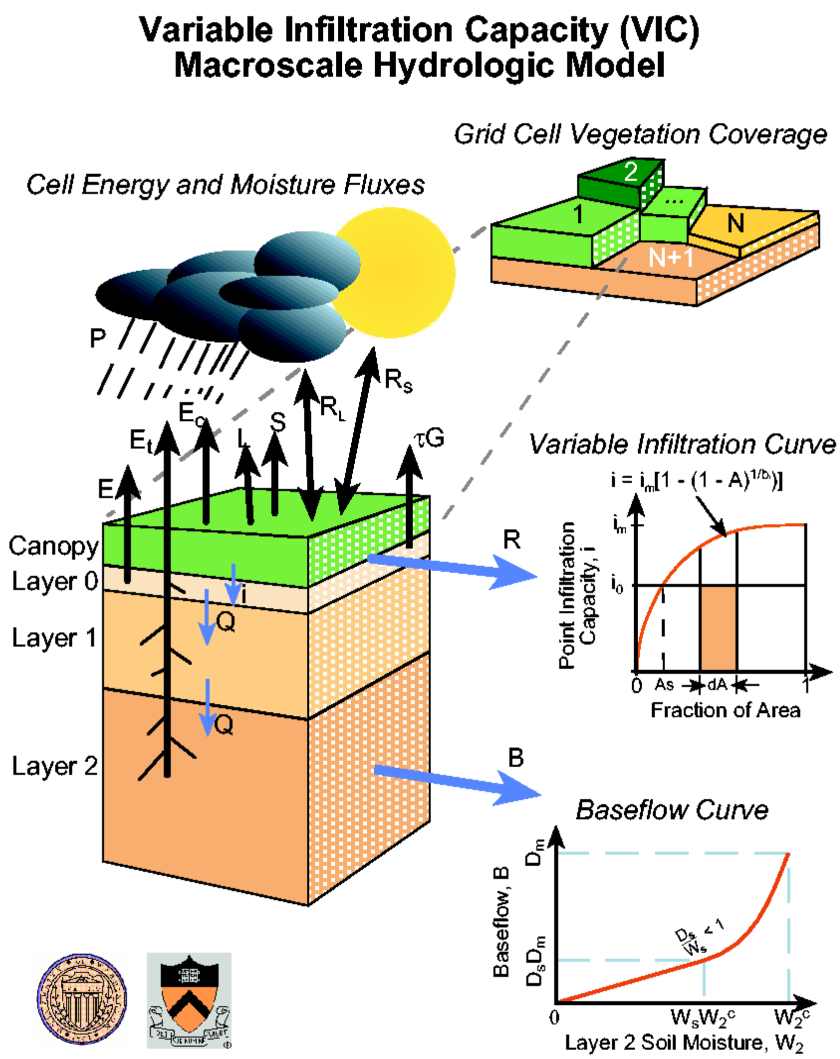


Figure 2 VIC model overview

As implemented here (offline, water balance mode), VIC is driven by daily inputs of precipitation, maximum and minimum air temperature, and windspeed (Chapter 3). Additional model forcings that drive the water balance, such as solar (short-wave) and long-wave radiation, relative humidity, vapor pressure and vapor pressure deficit, are calculated in a preprocessing step within the model. What makes the VIC model unique is its representation of the soil column and parameterization of the infiltration process, which impacts the vertical distribution of soil moisture in the model grid cell. The VIC model represents multiple vegetation types and 3 soil layers which allows for variable infiltration and evaporation. Potential evapotranspiration is calculated using a Penman Monteith approach (Maidment et al, 1993). VIC also contains a sub-daily (1-hour time step) snow model which follows the algorithm of Cherkauer and Lettenmaier 2003, Wigmosta et al. 1994, and Andreadis et al. 2009.

Subgrid elevation bands increase the ability to resolve snow processes within each grid cell. For the current application, an elevation band resolution of approximately 500m is imposed (less than 5 elevation bands in even the steepest locations). For each grid cell, the model calculates water balance variables (among others) such as evapotranspiration, runoff, baseflow, soil moisture, and snow water equivalent. A full list of output variables for this study is provided in Chapters 4 and 8. To calculate streamflow in larger basins, daily runoff and baseflow are used as input to an offline routing model (based on Lohmann et al. 1996).

Elsner et al. (2009) added additional calculations in the model to allow output of daily potential evapotranspiration (PET) for each model grid cell. PET is the amount of water that would be transpired by vegetation, provided unlimited water supply, and is often used as a reference value of land surface water stress in characterizations of climate interactions with forest processes (e.g., Littell et al. 2009). PET is calculated in the VIC model using the Penman-Montieth approach (Liang et al. 1996) and the user may choose to output PET of natural vegetation, open water, and PET of certain reference agricultural crops.

These types of PET differ by the assumptions made in the Penman Monteith equation. Generally, the Penman Monteith equation requires information including solar radiation, air temperature, windspeed, as well as vegetation characteristics such as leaf area index (LAI), aerodynamic resistance and vegetation resistances, including architectural and canopy resistance. PET values differ in their assumptions of albedo, LAI, aerodynamic resistance and vegetation resistances. Table 1 summarizes the differences in these variables and they are further described below. For all PET types, windspeed height is fixed at heights well above vegetation. Also, aerodynamic resistance is dependent on vegetation type, so for reference crop PET, aerodynamic resistances are fixed for these crop types.

Table 1 Summary of potential evapotranspiration variables and assumptions in their calculation.

PET variable	Albedo	Vegetation Resistence
PETveg (natural vegetation, no water limit)	Varies by vegetation type and month	Rs, Rarc, Rc, LAI varies by vegetation type
PETh2o (open water surface - fixed albedo)	0.1	Rs=0 s/m Rarc=0 s/m LAI varies by vegetation type
PETvegnocr (natural vegetation, no water limit, no vegetation resistance)	Varies by vegetation type and month	Rs=0 s/m Rarc=0 s/m Rc=0 s/m LAI = 1.0
PETtall (Tall reference crop – alfalfa)	0.23	Rs = 100 s/m Rarc = 25 s/m LAI = 4.45
PETshort (Short reference crop - short grass)	0.23	Rs = 100 s/m Rarc = 25 s/m LAI = 2.88

Natural vegetation PET (PETveg) assumes the albedo, vegetative resistance, and aerodynamic resistances of natural vegetation, as if the vegetation is in place as is, and the plant evapotranspiration is not limited by water supply. The windspeed height is defined as the sum of the wind height, displacement, roughness, and 10 meters (default used so windspeed height is adequately high above vegetation).

Open water evapotranspiration (PETh2o) is similar to pan evaporation that is often recorded at reservoirs. This variable assumes that the albedo, or fraction of light that is reflected from the surface, is 0.1. The aerodynamic resistance is set equal to that of a short reference crop. The vegetative resistances (stomatal and architectural) are set to zero. It appropriate only to evaluate this variable during summer months when open water would not be frozen and snow-covered, as this causes some of the assumptions in this calculation to be invalid.

Short reference crop PET (PETshort_crop) is the PET assuming the only present vegetation type is grass. The height of grass is set to 0.12 meters. The albedo for grass is assumed to be 0.23. The vegetation resistance is assumed to be 100 s/m for stomatal resistance and 25 s/m for architectural resistance s/m.

Tall reference crop PET (PETtall_crop) is the PET assuming the only present vegetation type is alfalfa. The height of alfalfa is set to 0.5 meters. The albedo, resistance factors, and windspeed height are assumed to be the same as for the short reference crop (grass).

Natural vegetation PET with no canopy resistance (PETvegnocr) is similar to PETveg, however, we assume that the canopy does not exist and therefore the windspeed is not impacted by vegetation. In this case, vegetation resistances are effectively set to zero. Albedo, aerodynamic resistance, and windspeed height are the same as for PETveg.

2.2 Description of Climate Change Scenarios

In this chapter, we evaluate simulations of the VIC model under three types of climate change scenarios for the 2020s (30 year average centered on 2025), 2040s (30 year average centered on 2045), and 2080s (30 year average centered on 2085). The first type of climate change scenario is similar to that using the approach taken by Elsner et al. 2009, in which projected average monthly changes in precipitation and temperature are applied as perturbation factors to the historical model forcing dataset on a daily basis. This approach is often referred to as the delta method approach.

The second type of climate change scenario is typically called the transient scenario and follows the approach of Wood et al. 2004 and Salathé et al. 2007, in which GCM simulations are bias corrected and statistically downscaled to the spatial resolution of the hydrologic model (in this case VIC). The result is a daily timestep gridded dataset for the CRB (including coastal drainages in Washington and Oregon) from approximately 2000 through 2099.

The third type of climate change scenario is introduced in this report and is a hybrid method between the delta method approach and the statistical downscaling method. In this method, GCM scenarios are spatial downscaled to the resolution of the VIC model (1/16th) degree and at a monthly timestep. The historical dataset at a daily timestep is aggregated to monthly timestep and bias corrected against the spatially downscaled dataset to produce a new dataset with the realistic variability of storms from the historical dataset and the climate change signals of the spatially downscaled dataset, including projected changes in climate variability and magnitude of change. For further details on the development of the three types of climate change scenarios, refer to Chapter 4 on GCM downscaling methods and applications.

2.3 Soil, Vegetation, and Snowband parameters

In addition to timeseries forcings, the VIC model uses as input four parameter files which are static and predefined: the soil parameter file, vegetation parameter file, vegetation library, and snowbands parameter file. Each parameter file contains information specific to each model grid cell, while the vegetation library contains general information for vegetation types that may be referenced by the vegetation parameter file.

The soil parameter file contains information such as soil layer, infiltration parameters, and many others which are defined by Liang et al. 1994 and 1996. Typical VIC model calibration parameters may be found in the soil parameter file and these include middle and bottom layer soil depths as well as parameters that define the variable infiltration capacity function. The soil parameter file developed for the 1/8th degree VIC implementation of the PNW (Maurer et al. 2002) was used as a basis for the 1/16th degree soil parameter file used in this study, although some parameters were recomputed at

$1/16^{th}$ degree including average grid cell elevation, annual average air temperature, annual average precipitation, and average July temperature.

Typically, model calibration includes the assignment of a single soil layer depth across the calibrated watershed, regardless of whether the grid cell is located in a steep mountainous region or in a flat low lying floodplain. In an effort to incorporate more realistic soil depths, in this study we have fixed the top and middle soil depths to 0.1 and 0.3 meters, respectively, and applied the soil depth algorithm within the DHSVM model to calculate the soil depth of the bottom VIC model soil layer (Wigmosta et al 1994). Simply, the algorithm uses a predefined soil depth range for the watershed (in this case 0.5 to 2.5 meters) and a DEM to assign a soil depth to each grid cell within this range, based on mean cell elevation and aspect (as computed from the DEM). The resulting map of total soil depth for the PNW applied in this study is provided in Figure 3.

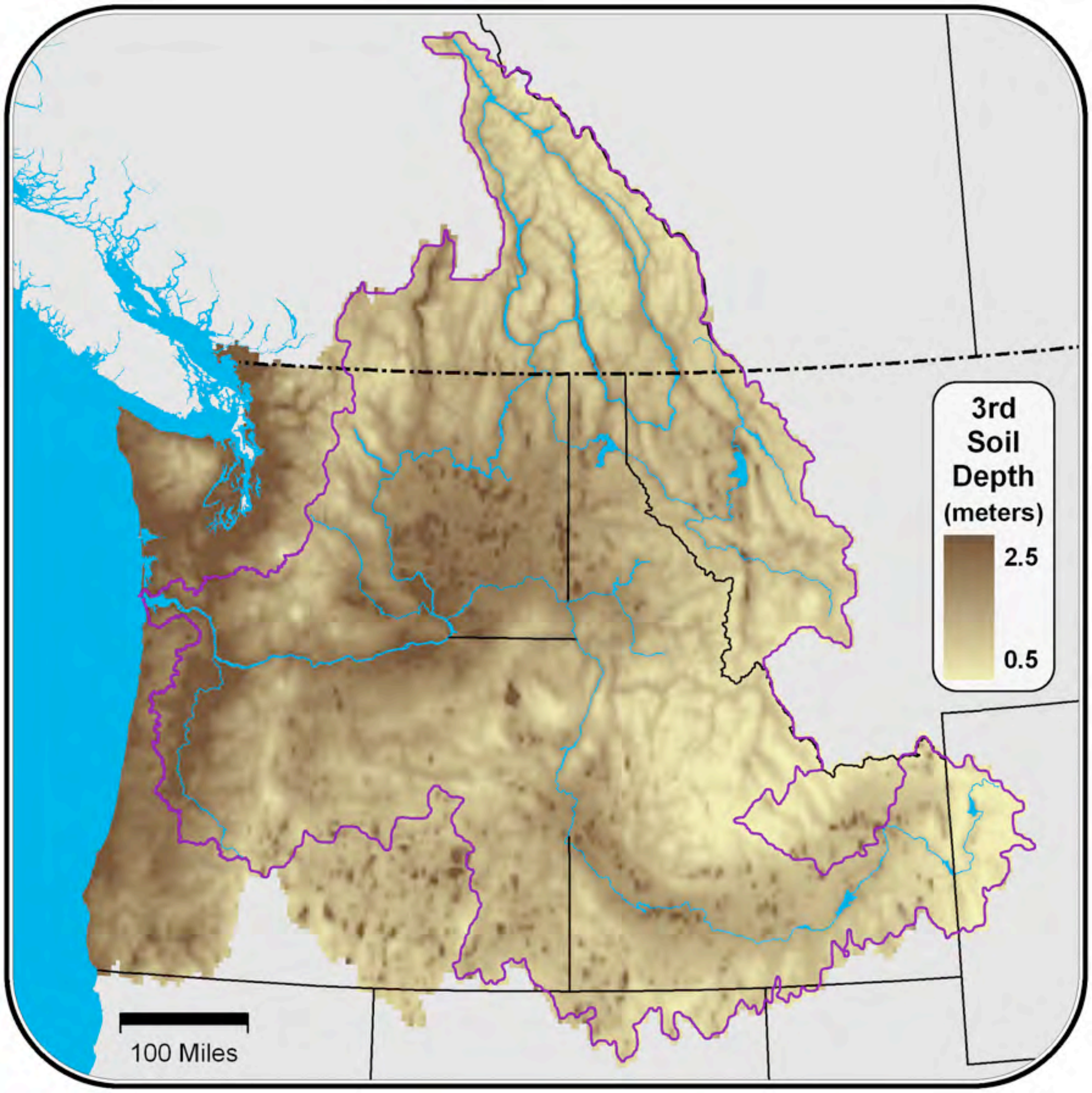


Figure 3 VIC model third (bottom) layer soil depths at 1/16th degree latitude longitude resolution.

The vegetation parameter file used in this study is based on preprocessed parameters from the LDAS (Land Data Assimilation System) dataset for the continental United States, which utilizes a vegetation classification scheme from the University of Maryland (UMD) (Hansen et al. 2000) at 1 km spatial resolution. Vegetation data at this scale were aggregated to produce vegetation parameters at 1/16th degree resolution. The vegetation library is also based on the UMD classification scheme.

The snowbands parameter file includes the definition of elevation bands within each VIC model grid cell. The number of elevation bands assigned for a grid cell is based on two criteria, namely a band may not have a maximum elevation range of more than 500 meters, with a maximum of 5 elevation bands per grid cell. For those cells where more that 5 bands would be required to accommodate the 500 meter range limit, the number of bands is set to 5 and the elevation ranges are equally distributed between them. Elevation bands are determined based on a 30 arcsecond (or approximately 1km) DEM.

2.4 Application of off-line streamflow routing model and routing network

As mentioned in section 2.1, the VIC model produces runoff and baseflow at each model grid cell for each model timestep. An off-line, or separate streamflow routing model, developed by Lohmann et al. 1996, computes streamflow at chosen locations based on convolution of runoff and baseflow. A predetermined routing network provides the upstream-downstream linkage between VIC model grid cells.

The routing network was developed based on the 30 arcsecond digital elevation model (DEM) from the U.S. Geological Survey (USGS) for the continental US (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30/hydro). A 1km digital streamflow layer was imprinted or "burned" into the DEM to clearly mark stream channels into the DEM (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30/hydro). Further processing steps using built in tools in ArcGIS Desktop were applied to develop the streamflow routing network at 1/16th degree spatial resolution to exactly match the resolution of the VIC model.

The 297 streamflow routing locations described in Chapter 3 (this report) were then located on the developed streamflow routing network and verified based on their true latitude-longitude location. Adjustments were made to streamflow site locations if the computed upstream watersheds area using the routing network was not within 10% of the cited watershed area by the USGS.

2.5 Model calibration

Calibration of the VIC hydrologic model was conducted using a similar approach to Matheussen et al. 2000, in which major sub-watersheds of the CRB were identified and routed streamflow at the sub-watershed outlets were calibrated on a monthly timestep to available natural (or unregulated) streamflow data. Calibration watersheds as well as model calibration and validation statistics are provided in Table 2 and error statistics include Nash Sutcliffe efficiencies (NSE) and R^2. A well calibrated model typically yields a NSE and R^2 higher than 0.7 (Liang et al. 1996; Nijssen et al. 1997).

Table 2 Summary monthly error statistics for VIC model calibration for 12 major watersheds.

Basins (gage)	**N-S model efficiency**	**R^2**
Columbia River at Revelstoke		
Calibration period (1975-1989)	0.76	0.80
Validation period (1960-1974)	0.76	0.80
Kootenay River at Corra Linn		
Calibration period (1975-1989)	0.89	0.89
Validation period (1960-1974)	0.93	0.93
Pend D'Oreille River at Waneta		
Calibration period (1975-1989)	0.88	0.91
Validation period (1960-1974)	0.85	0.93
Kootenai River at Libby		
Calibration period (1975-1989)	0.77	0.88
Validation period (1960-1974)	0.90	0.92
Columbia River at Priest Rapids		
Calibration period (1975-1989)	0.89	0.89
Validation period (1960-1974)	0.91	0.92
Yakima River at Parker		
Calibration period (1975-1989)	0.78	0.84
Validation period (1960-1974)	0.80	0.85

Clearwater River at Dworshak		
Calibration period (1975-1989)	0.77	0.82
Validation period (1960-1974)	0.68	0.86
Snake River at Milner		
Calibration period (1975-1989)	0.74	0.82
Validation period (1960-1974)	0.77	0.78
Columbia River at Ice Harbor		
Calibration period (1975-1989)	0.83	0.90
Validation period (1960-1974)	0.93	0.94
Willamette River at Portland		
Calibration period (1975-1989)	0.89	0.93
Validation period (1960-1974)	0.91	0.93
Columbia River at The Dalles		
Calibration period (1975-1989)	0.89	0.90
Validation period (1960-1974)	0.92	0.92

VIC model calibration was conducted using an autocalibration tool called MOCOM-UA developed by the Land Surface Hydrology group at the University of Washington, following the approach of Yapo et al. 1998. The code was improved upon by the Pacific Climate Impacts Consortium at the University of Victoria, British Columbia. This tool uses a multi-objective function and shuffle complex evolution procedure to optimize model calibration parameters to create a set of pareto (equally) optimal calibration parameters. The user may define the number of calibration parameters, the number of objectives on which to perform optimization, and the error statistics on which to base the objective function. The calibration implementation approach taken for this study includes 50 initial parameter sets to define the optimization parameter space, 25 parameter sets which advance forward in each evolution of optimization, 3 VIC model calibration parameters including Ds, Dsmax, and Ws, and 6 error statistics which define the multiple objective function: r^2, NSE, the logarithm of the NSE, annual volume error, mean hydrograph peak difference, route mean squared error (RMSE), and number of sign changes when subtracting the simulated monthly hydrograph from the observed natural hydrograph. The optimization function can be generally stated by the following relationship:

Min F = {-NSE(Q), -logNSE(Q), VolErr(Q), -R2(Q), PeakDiff(Q), RMSE(Q), NumSC(Q)}

Where,

NSE(Q) = Nash Suttcliffe Efficiency

logNSE(Q) = logarithm of Nash Suttcliffe Efficiency

VolErr(Q) = annual volume error (in 1000AF)

R2(Q) = r^2

Peak Diff(Q) = mean hydrograph peak difference

RMSE(Q) = rout mean squared error

NumSC(Q) = number of sign changes

Model calibration used a split sample approach in which calibration was performed for each of the 11 primary watersheds over a 15 year period (typically water years 1975-1989) and model validation was performed over a separate 15 year period (typically water years 1960-1974). Calibration and validation periods were chosen to include a range of streamflow conditions with which to test model performance. Other parameters (e.g. simulated SWE or soil moisture) were not used to further constrain model parameters. However, previous studies comparing VIC simulated SWE with observations (Andreadis et al. 2009) and soil moisture with observations (Maurer et al. 2002; Mote et al. 2005)), indicate that the model successfully simulates grid level processes that are appropriately sensitive to climate forcing and other factors.

Model calibration parameters were further validated at smaller watershed scales where naturalized flow data were available. Results of model calibration and validation are presented in Section 1.5.

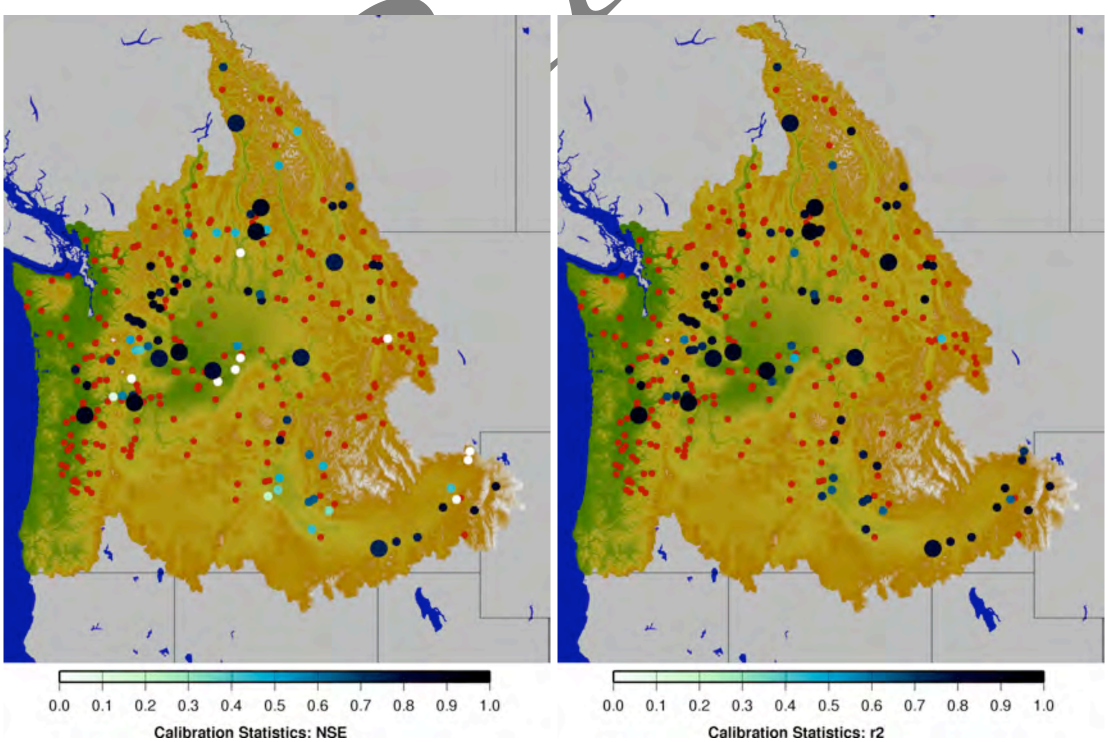
A number of calibrations tests were performed prior to calibration to inform and help refine the process. For example, a test run of the Yakima basin with and without use of the variable soil depth map indicated that map caused a decrease in the Nash Suttcliffe Efficiency (0.71 down to 0.57) and RMSE values (114.9 up to 133.2 kaf). The coefficient of determination, R^2, did not change (0.94).

Additional test runs were performed on the Naches watershed, a subbasin of the Yakima River basin, to investigate whether calibration of multiple parameters simultaneously is advantageous over successive calibrations where certain parameters are calibrated then fixed while additional parameters are calibrated. Specifically, we tested the impact of 1) calibrating first the infiltration parameters (bi, Ds, Dsmax, and Ws) and subsequently the bottom soil layer depth as well as 2) the impacts of calibrating all 5 parameters simultaneously. We found the results Nash Suttcliffe Efficiencies and RMSE were the same (0.56 and 54.6kaf, respectively), while the R^2 was improved in test (2) over (1), with values of 0.75 and 0.67, respectively. Although this test did not include all scenarios, it did indicate that similar error statistics may be gained through both approaches and autocalibration run time is highly dependent on the number of parameters to be optimized. Successive calibrations with a smaller parameter space may prove to be a significant long-term time savings. Further testing is needed to evaluate this hypothesis.

Non-parametric, statistical bias correction techniques (Snover et al. 2003) have also been employed at sites for which naturalized or modified flow was available to remove systematic bias from the streamflow simulations. These approaches provide an alternative to traditional calibration techniques (such as described above) and are particularly effective when errors in the hydrologic simulations are likely to be related to errors in meteorological driving data sets (a frequent occurrence at relatively small spatial scales). Chapter 8 describes these data processing steps in greater detail.

2.6 Basin Scale Model Evaluation

VIC model calibration was conducted over 11 subbasins of the Columbia River as described in Section 1.4 and illustrated in Figure 1. The time period used for calibration was water year 1975 to 1989 (October 1974 through September 1989). This 15 year period encompasses a range of wet, dry, and average years to test VIC model performance under these conditions. A separate 15 year period was used for model validation, namely water year 1960 to 1974 (October 1959 through September 1974). This period also encompasses a range of climatic and streamflow conditions under which we can evaluate VIC model performance. Error statistics used to test model performance included Nash-Sutcliffe efficiency, the logarithm of the Nash-Sutcliff efficiency, annual volume error, R^2, mean hydrograph peak difference, route mean squared error (RMSE), and number of sign changes. The NSE and R^2 reflect the ability of the VIC model to simulate proper magnitude and timing of streamflow without influence from existing model bias. For this reason, these statistics for each site for which observed natural streamflow was available are illustrated in Figure 4. In the figure, the larger points represent those primary sites that were used for model calibration and validation.



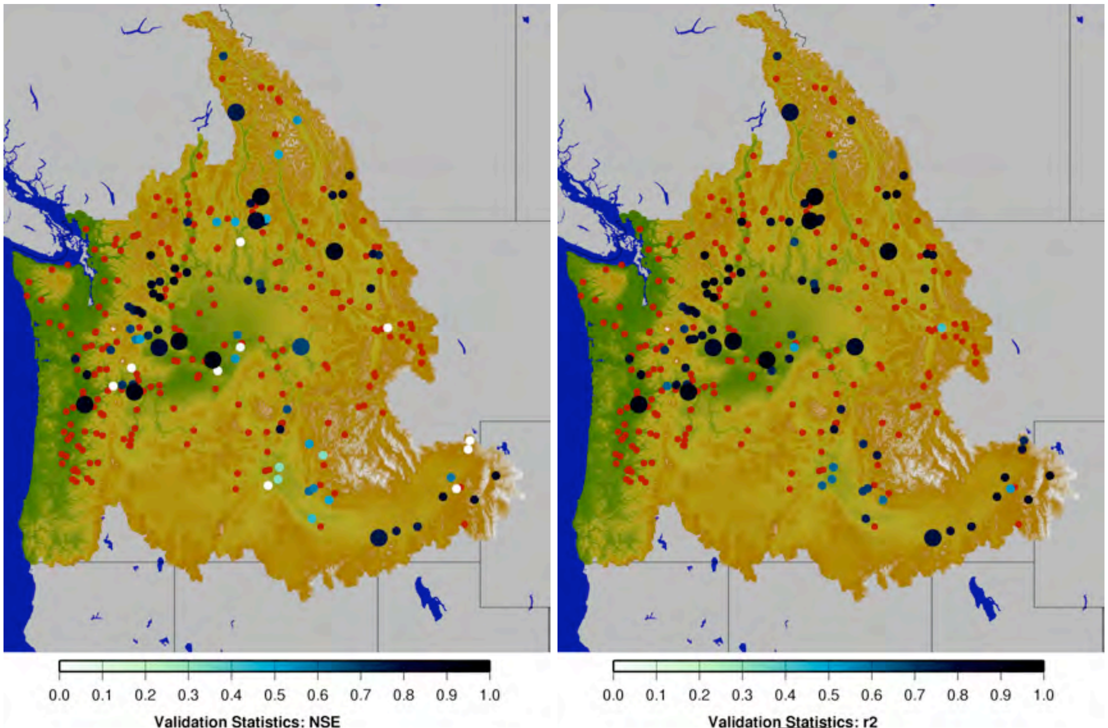


Figure 4 Summary map of 80 of the total 297 streamflow locations where error statistics between simulated and naturalized flow were computed. The two top panels show Nash Sutcliffe Efficiency (left) and R2 (right) for the calibration period, while the two lower panels show Nash Sutcliffe Efficiency (left) and R2 (right) for the validation period. Red locations indicate those sites where naturalized flows were not available.

We assume that VIC model calibration parameters determined for 11 major subbasins of the Columbia River are appropriate for all subbasins within them. However, we might expect that smaller subbasins have different hydrologic characteristics than the large watershed that contains it and therefore would require unique calibration parameters for proper simulation. We did a test of three subbasins of the WANET basin (Pend Oreille River at Waneta Dam): BLAGA (Little Blackfoot River near Garrison), SWANR (Swan River near Big Fork), and BITWF (W Fork Bitterroot River near Conner). NSE and R^2 parameters for the calibration parameters at WANET are 0.879 and 0.910, respectively.

Table 3 summaries these error statistics for the three subwatersheds using two sets of calibration parameters: those using the WANET calibration parameters and those determined through independent calibration of the three watersheds. For these subbasins, there is little improvement in error statistics through calibration of small watersheds independently and additionally, the time savings in model calibration time help to justify use of calibration parameters at larger scales. In the case of the WANET basin, the calibration of this watershed is complicated by possible bias in meteorological data (as implied by less than ideal calibration error statistics), which would limit calibration success potential for subwatersheds within it. Potential biases in meteorological data are generally not compensated by adjusting calibration parameters.

Table 3 Comparison of error statistics (NSE and R^2) for three subbasins of the WANET calibration basin. Top set of statistics use WANET calibration parameters, while the lower set uses independent calibration parameters for each subbasin.

Sub-basin	**SWANR**	**BLAGA**	**BITWF**
Calibration Parameters	Ds=0.375 Ws=0.872 Dsmax=2.298	Ds=0.375 Ws=0.872 Dsmax=2.298	Ds=0.375 Ws=0.872 Dsmax=2.298
NSE	0.780	0.487	0.577
R^2	0.801	0.640	0.666
Calibration Parameters	Ds=0.543 Ws=0.963 Dsmax=5.514	Ds=0.017 Ws=0.347 Dsmax=6.788	Ds=0.363 Ws=0.434 Dsmax=1.254
NSE	0.827	0.559	0.579
R^2	0.837	0.643	0.657

3. Key Findings/Discussion

Although predictions of changes in winter precipitation over the PNW have differed somewhat among recent IPCC reports (the 1995 report suggests an increase, whereas the 2001 report indicates only modest changes and the 2007 report indicates increases of a few percent by the 2040s and up to 8 percent by the 2080s, compared with the 1970-1999 climatological mean), warmer temperatures in all previous assessments have led to projections of reduced snowpack, and transformation of sensitive watersheds from being fed by a mix of rain and snow to predominantly rain. Other impacts common to previous studies of hydrological impacts of climate change in the PNW include earlier spring peak flow and lower summer flows. A wide range of hydrologic products are available on the project web site (www.hydro.washington.edu/2860/), as described in Chapter 7, 8 and 9, but we provide an overview of some key hydrologic impacts over the entire CRB.

3.1 Snowpack and streamflow

The PNW is typically characterized as having three representative types of watersheds, dictated mainly by the form of precipitation they receive throughout the year. These include rain dominant watersheds, were most annual precipitation falls as rain; transient watersheds, where annual precipitation is a mix of rain and snow; and, snow dominant, where a majority of annual precipitation falls as snow in the cool season. Figure 5 illustrates this classification through the metric of the ratio of peak snow water equivalent to October through March precipitation. This metric is further described in Elsner et al. 2009. Generally, lower elevation coastal watersheds are classified as rain dominant, while watersheds in the headwaters of the Columbia River basin are classified as snow dominant. Much of the interior Columbia basin consists of mid-elevation transient watersheds. These are particularly sensitive to climate change because small changes in temperature can significantly change the balance of precipitation falling as snow versus rain.

Using traditional delta method climate change scenarios, we illustrate how projected changes in precipitation and temperature are likely to impact snowpack in the PNW, and thus alter the rain/snow balance. Figure 6 illustrates mean projected changes in SWE on April 1 for three future time periods, the 2020s, 2040s, and 2080s, and two greenhouse gas emissions scenarios, A1B and B1. April 1 SWE is a common indicator of summer water supply in the PNW and is therefore a useful metric for evaluating projected change. Results show that snowpack throughout the region is likely to experience modest declines through the 2020s (compared with the historical 1916-2006 mean) of about 18%, with increasingly significant declines further into the 21st century. In general, the Canadian portion of the Columbia River basin will be less significantly impacted than the remaining parts of the basin. Also, due to its assumption of higher future greenhouse gas emissions, the A1B scenario generally indicates greater impacts to hydrology than the B1 scenario.

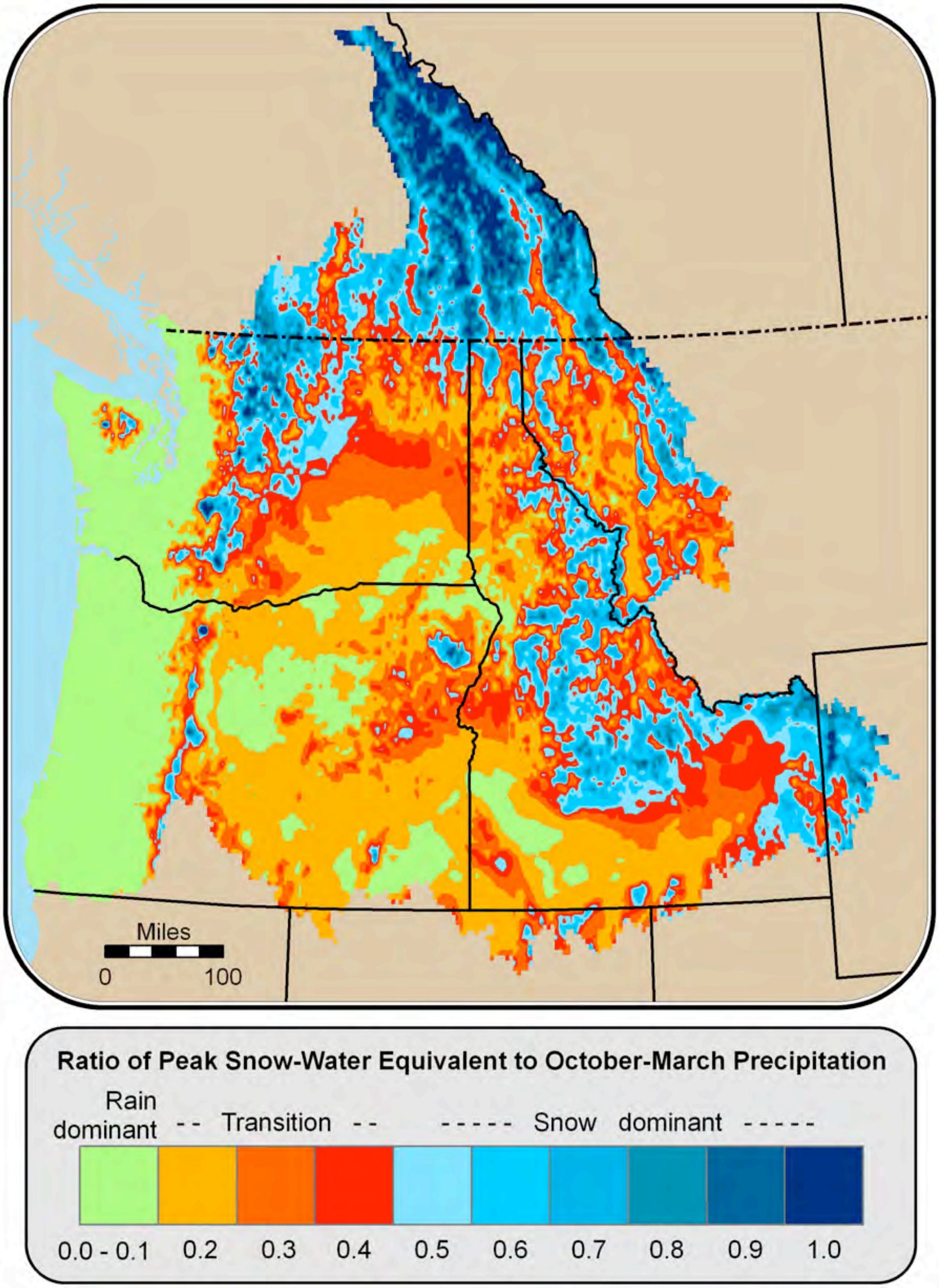


Figure 5 The average ratio of peak VIC model simulated snow water equivalent (SWE) to October – March precipitation for the historical period (water year 1917-2006)

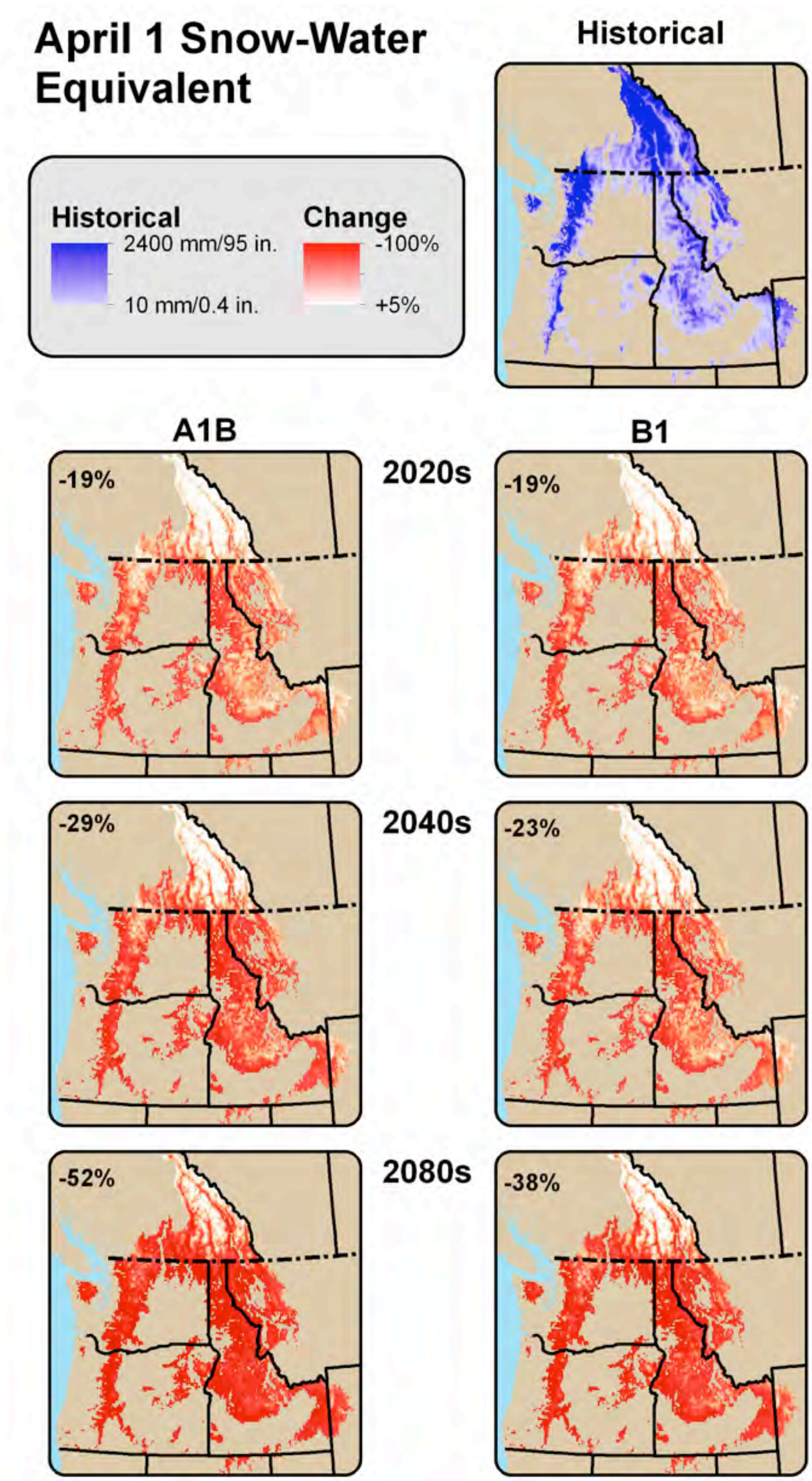


Figure 6 Summary of historical (mean 1916-2006 water years) April 1 snow water equivalent and percent (%) changes in April 1 snow water equivalent projected using A1B (left) and B1 (right) emissions scenarios for the 2020s, 2040s, and 2080s compared with historical. Domain average percent change is reported in the upper left corner of each figure panel.

Significant declines in snowpack have important implications for regional streamflow, as illustrated by Figures 7 and 8. Figure 7 illustrates mean historical (water year 1916-2006) and mean projected runoff hydrographs using the hybrid delta method approach for the 2040s for three sites: the Columbia River at the Dalles, the Snake River at Milner, and the Yakima River at Parker. Similar to figure 7, figure 8 summarizes results from the transient climate change scenarios for the same three basins and future time period. Runoff presented in these figure represents mean flow across the watersheds and has not been routed through stream channels. Still, these hydrographs are illustrative of the changes in streamflow volume and timing projected for the 2040s at these sites. The Columbia River as a whole and the Snake River above Milner dam may be considered as snow dominant watersheds because runoff generally peaks in late spring as snowmelt is the main contributor to runoff. In the 2040s for these watersheds, both hybrid delta and transient scenarios project modest increases in winter flow, decreases in summer flow, as well as a shift in the peak of the hydrographs earlier in the season. The range of transient scenario projections is generally tighter than the hybrid delta method scenario projections. In part, this reflects the smaller number of transient projection ensembles (7), compared with hybrid delta projection ensembles (10). Furthermore, the 7 best GCMs were chosen for the transient scenarios, based on their ability to reproduce 20th century climate (refer to Chapter 4), while the 10 best were chosen for the hybrid delta scenarios.

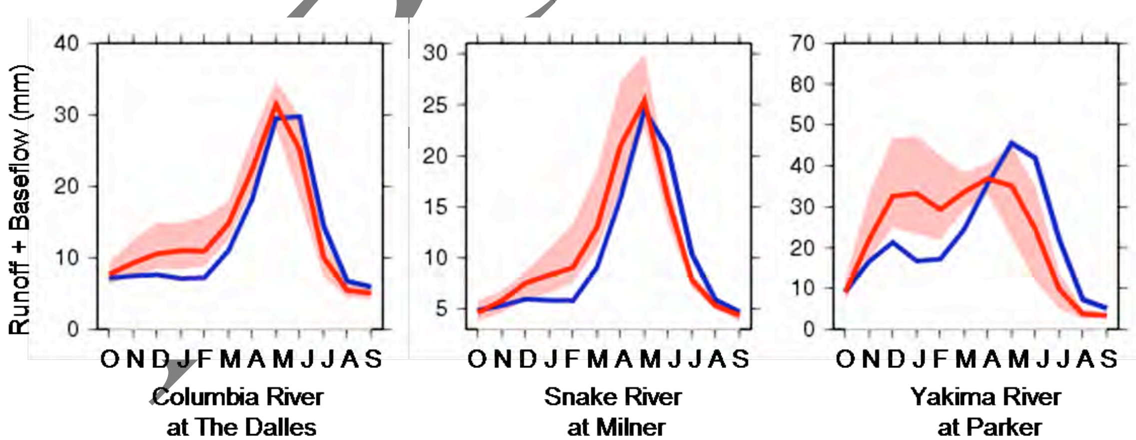


Figure 7 Projected combined flow (runoff + baseflow) in millimeters for the 2040s A1B scenario at three sites in the Columbia River basin. The blue line represents the historic monthly mean flow (water years 1916-2006) while the red line represents projected monthly mean flow averaged across 10 A1B hybrid delta method scenarios for the 2040s (representing mean 2030-2059 climate). The red band represents the range of projections from the 10 individual A1B hybrid delta method scenarios.

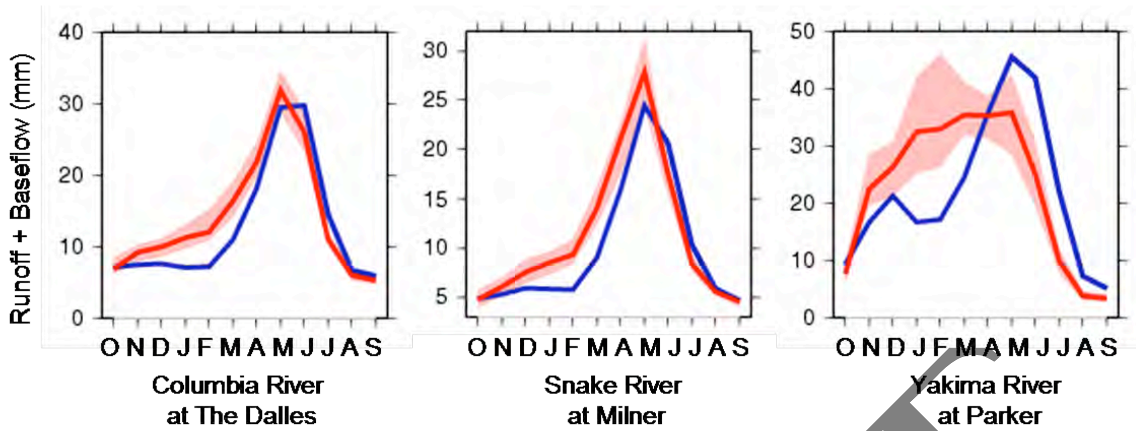


Figure 8 Projected combined flow (runoff + baseflow) in millimeters for the 2040s A1B scenario at three sites in the Columbia River basin. The blue line represents the historic monthly mean flow (water years 1916-2006) while the red line represents projected monthly mean flow averaged across 7 A1B transient scenarios for the 2040s (representing mean 2030-2059 climate). The red band represents the range of projections from the 7 individual A1B hybrid delta method scenarios.

3.2 Potential and actual evapotranspiration

Figure 9 summarizes mean historical (1916-2006) summer PET (average sum of June, July, and August) and percent change in projected summer PET for the 2020s, 2040s and 2080s using A1B and B1 emissions scenarios and the traditional delta method approach. Historically, average summer PET ranges from 130 to 630mm, with higher PET in southeastern Oregon and east of the Cascade mountains. The western flanks of the Cascades and the interior Columbia and Snake basins have modest to lower PET, while south central Oregon has the lowest PET in the region. These variations in PET across the region appear to be largely dependent on vegetation type. Regions with lowest summer PET historically are typically classified as shrublands, while regions with highest summer PET historically include wooded areas, both deciduous and evergreen.

Projected changes in average summer PET show growing summer PET in the coastal and mountainous parts of the domain and no change to decreases in PET in the interior Columbia and interior Snake basins. The magnitudes of these changes increase (in both positive and negative directions) further into the future and impacts using A1B scenarios are generally more significant than those using B1 scenarios. Increases PET are driven mainly by increases in VPT (vapor pressure deficit), while decreases in PET are driven mainly by increases in outgoing longwave radiation due to projected temperature change and higher albedo of shrubland and cropland vegetation.

Figure 10 summarizes mean historical (1916-2006) summer AET (average sum of June, July, and August) and percent change in projected summer AET for the 2020s, 2040s, and 2080s using A1B and B1 emissions scenarios and the traditional delta method approach. Historically, mean summer AET ranges from 24mm to 440mm for the PNW, with the greatest AET occurring along the coast and mountainous parts of the region. The lowest AET occurs in the interior Columbia basin, central Oregon, and the interior Snake River basin. Regions if higher AET closely correspond with the forested parts of the region.

Projected AET is likely to increase in western Washington and along windward slopes of the mountain ranges and decrease in most of the other parts of the PNW, in particular on the leeward slopes of the mountain ranges. The magnitude of these changes is projected to increase further into the future and A1B scenarios generally indicate greater changes than the B1 scenarios. Decreases in AET over much of the region correspond with overall decreases in summer precipitation. Despite decreases in summer precipitation, the mountains are projected to experience increases in AET which is likely due to increased water availability through enhanced snowmelt and increased soil moisture.

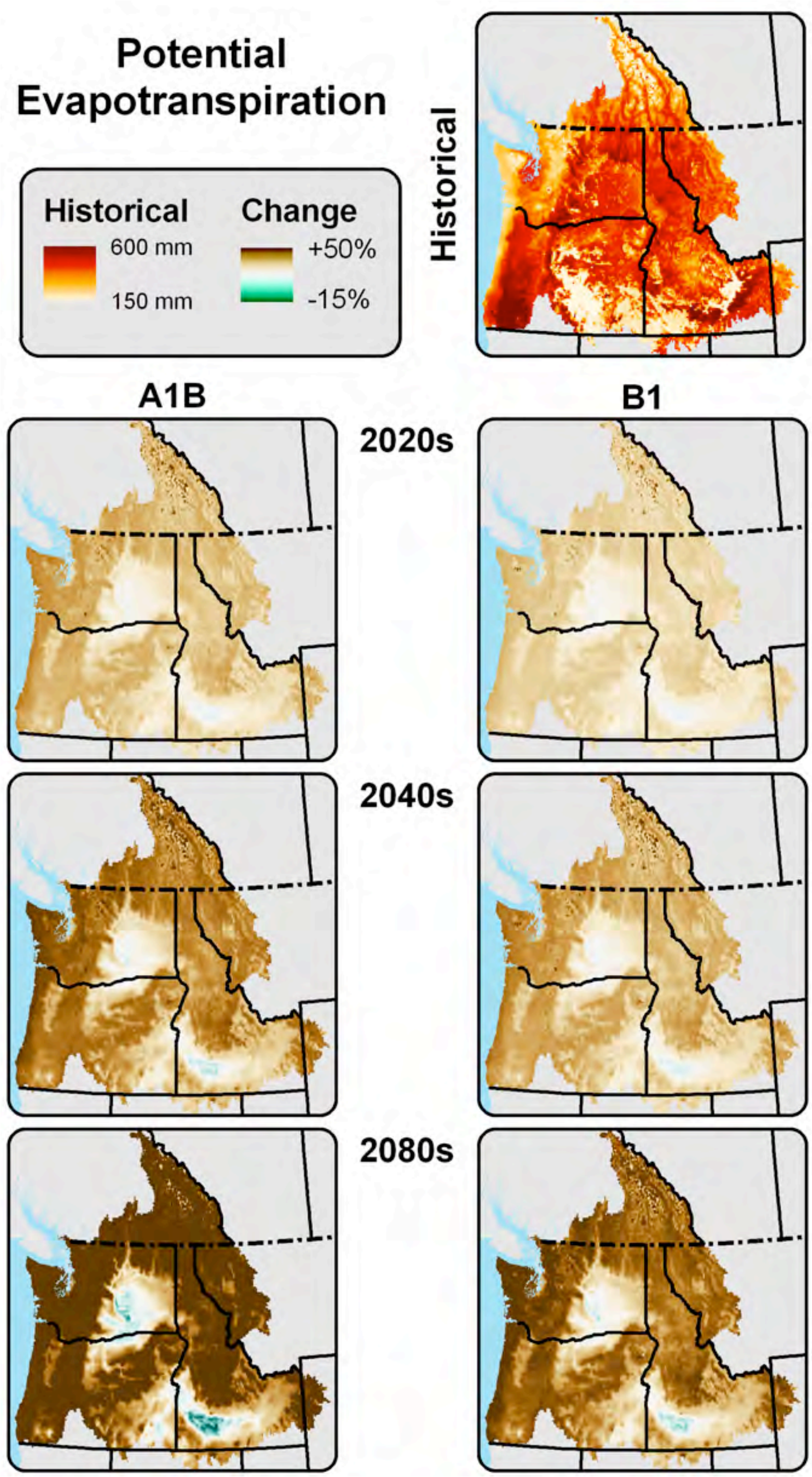


Figure 9 Summary of historical (mean 1916-2006 water years) total summer (July, August, September) potential evapotranspiration and percent (%) changes in summer potential evapotranspiration projected using A1B (left) and B1 (right) emissions scenarios for the 2020s, 2040s, and 2080s compared with historical.

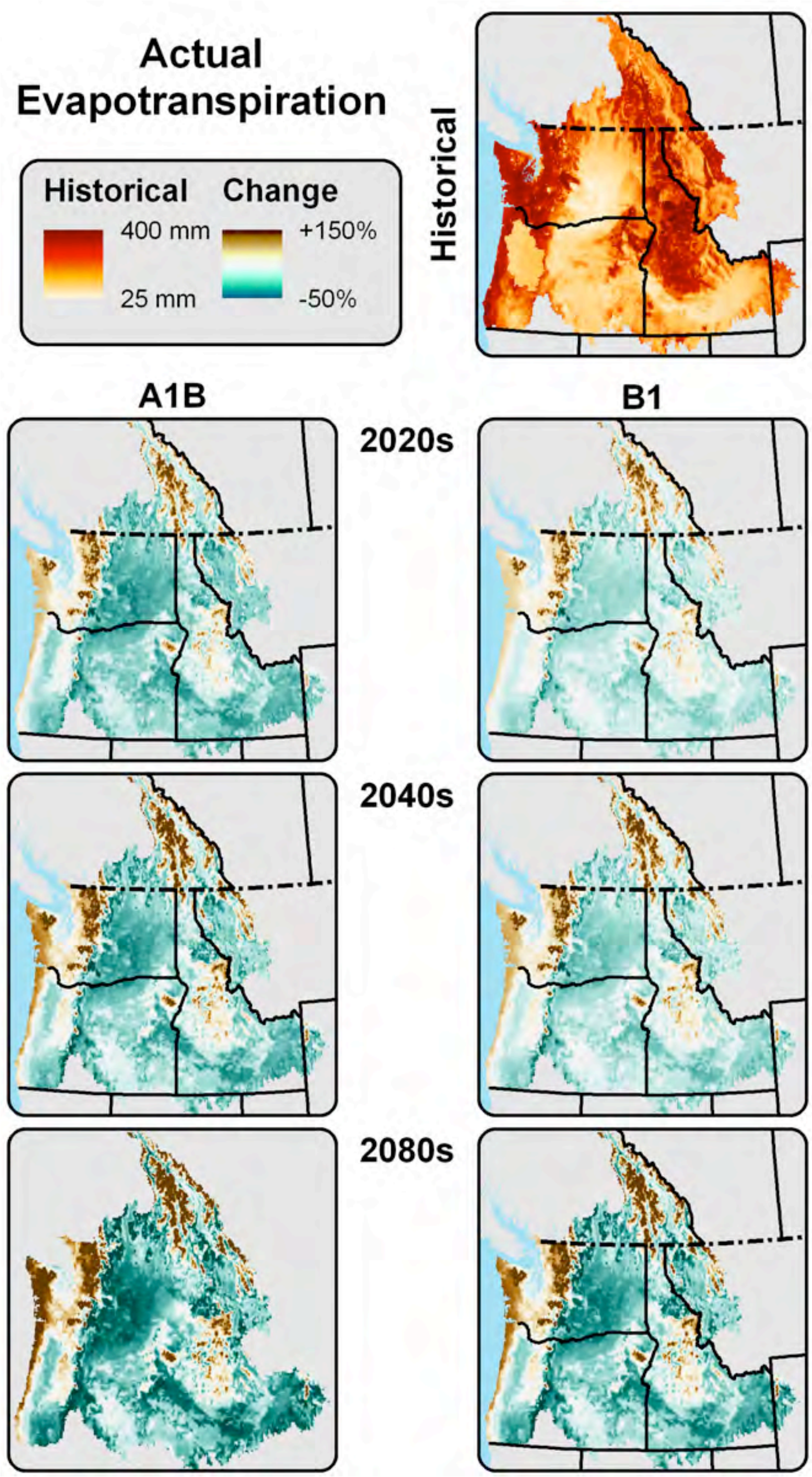


Figure 10 Summary of historical (mean 1916-2006 water years) total summer (July, August, September) evapotranspiration and percent (%) changes in summer evapotranspiration projected using A1B (left) and B1 (right) emissions scenarios for the 2020s, 2040s, and 2080s compared with historical.

4. Conclusions

The VIC macroscale hydrologic model was calibrated and implemented at 1/16th degree spatial resolution over the greater Columbia River basin (Columbia River watershed plus coastal drainages in Washington and Oregon) for historical period 1915-2006 and three types of projected climate change scenarios. These scenarios include 19 hybrid delta scenarios (10 for A1B and 9 for B1 greenhouse gas emissions scenarios) for three future time periods, 2020s, 2040s, and 2080s; 14 statistically downscaled continuous transient simulations for generally 1950-2099 (7 for A1B and 7 for B1); and, 2 composite delta method scenarios for the 2020s, 2040s, and 2080s (1 for A1B and 1 for B1).

In this chapter, we summarized our methodology for model calibration and validation; we described additional output variables offered through this implementation (namely five forms of PET) and array of climate change scenarios available; and, finally we summarized some of the key information available through this study, which is now available through an online database. The results illustrate that climate change is significantly affecting the water resources in the Columbia River watershed and will continue to do so through this century. Reduced winter snowpack and changes in the timing and availability of water to plants and streams have implications across many sectors. The datasets we provide offer a common set of tools which are a useful tool for evaluating impacts as part of independent regional climate change studies.

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Fine Scale Hydrologic Model Implementation

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1. Introduction

Hydrologic model output variables, including streamflow, snow melt timing, and stream temperature, are sensitive to the resolution and characteristic of the model utilized. As the need for simulations of specific parameters in certain river basins increases so does the need for the resolution and precision of the hydrologic model.

One common approach to large-scale hydrologic studies is the application of the Variable Infiltration Capacity (VIC) land surface hydrology model forced by gridded observed meteorological variables. This model has most recently been implemented at 1/16 degree latitude-longitude resolution (Elsner et al. 2009). However, this spatial resolution does not adequately represent hydrologic processes in small basins. For this reason the Distributed Hydrologic Surface Vegetation Model (DHSVM) (Wigmosta et al. 1994) which explicitly represents the effects of topography and vegetation on water fluxes through the landscape has been implemented in 5 sub basins of the Columbia River. DHSVM is typically applied at high spatial resolutions on the order of 100 m for watersheds up to 100,000 km2 and at sub-daily timescales for multi-year simulations. This distributed hydrologic model has been applied predominantly to mountainous watersheds in the Pacific Northwest in the United States. Results from DHSVM for these watersheds are compared with those from the VIC model.

DHSVM, as with any distributed hydrologic model, requires extensive information about the simulated basin. The first type of information is static data and can be divided in three main categories: elevation, vegetation cover and soils. The second type is dynamic, or timeseries, information which includes meteorological data that can be obtained from weather stations or derived from others models. In the 5 sub basins modeled, observing stations do not have sufficiently long records or do not exist in a spatially relevant location. Therefore, gridded products provide the spatial coverage that observing stations may lack. In these cases the same meteorological data that feed VIC was used to implement DHSVM. However, errors in precipitation forcing data derived from gridded data impact the effectiveness of the results and require calibration. At the same time all the information required by the DHSVM implies a longer time of implementation and computation compared with a macroscale model like VIC.

In contrast with VIC which parameterizes topography DHSVM consists of computational grid cells centered on Digital Elevation Model (DEM) elevation nodes, which explicitly represent the effects of topography in the basin. DEM data are used to define absorbed shortwave radiation, precipitation, air temperature, and down-slope water movement. One more important difference with VIC where each cell is assumed to be big enough to remain isolated from others is that in DHSVM each cell may exchange surface and subsurface water with its neighbors resulting in a three-dimensional redistribution across the basin. This water is routed across the basin using the defined stream channel network.

In this study, we implemented DHSVM v2.4 developed by Wiley (2009 in prep). Some modifications to the code in comparison with previous versions include the addition of a deep groundwater layer, expansion of surface and subsurface flow paths from 4 to 8 directions, allowance of the re-infiltration of water from the stream channel network back into the soil layer, the division of surface flows resulting from runoff from impervious surfaces by the fraction of impervious area, and the calculation of water temperature within the channel network. For a more complete description of these changes see Wiley (2009 in prep).

The sub-basins were the model was implemented are: Naches (2875 km2); Upper Yakima (4144 km2); Walla Walla (4293 km2); Methow (4620 km2) and West Kettle (1870 km2). For these sub-basins 60 different climate change scenarios were run based on the hybrid delta downscaling method discussed in Chapter 4.

2. Approach/Methods

2.1 The Distributed Hydrology Soil Vegetation Model

The Distributed Hydrology-Soil-Vegetation Model (DHSVM; Wigmosta et al., 1994; Wigmosta and Lettenmaier, 1999) is a spatially explicit hydrologic model that accounts for the physical processes affecting the movement of water on and through the land surface with a distributed, deterministic approach. In general, the model dynamically represents the spatial distribution of evapotranspiration, snow cover, soil moisture, and routed runoff across a watershed (Wigmosta et al., 2002). The digital elevation model (DEM) is the base for the model physical processes and DHSVM can solve full water and energy balance equations at the resolution of a DEM. The typical spatial resolutions for model applications range from 30-200 m (VanShaar et al., 2002). The DEM resolution drives the topographic controls that model: absorbed solar radiation, precipitation, air temperature, and downslope water movement (Wigmosta et al., 1994).

The model relies in a two-layer vegetation representation and a multi-layer soil profile for each pixel within the watershed boundary. For each pixel any combination or number of individual soil and vegetation classes may be incorporated, thereby enhancing the ability of the model to represent basin characteristics. The model operates at the same time step than the meteorological inputs, allowing as fine as 1-hr temporal resolution.

DHSVM incorporates a sophisticated two-layer snow accumulation and ablation model which relies in an energy balance that includes the effects of local topography and vegetation cover (Wigmosta et al., 1994). Surface and subsurface flow routing algorithms channel water to the watershed outlet and allow grid cells to exchange water with adjacent neighbors (Wigmosta et al., 2002). DHSVM inputs can be divided into three separate groups: 1) spatial data including raster and vector inputs, 2) meteorological time series data, and 3) associated files that serve as look-up tables during the modeling.

Spatial data inputs include a digital elevation model, a watershed mask, and grids of the soil type, soil depth and vegetation type. The stream and road networks are included as vector data. The model forcings are time-series of meteorological variables, primarily precipitation, temperature, short and long-wave radiation, relative humidity and wind. The various text file look-up tables provide physical details about the types of meteorological, soil, and vegetation data used. DHSVM utilizes a cell-by-cell approach to move water through the hydrologic system.

A more detailed description of the individual modules within the main DHSVM follows.

2.1.1 Evapotranspiration

DHSVM model evapotranspiration (ET) utilizing a potential ET rate and a Penman-Monteith approach, the model represent the canopy or overstory and understory with a two-layer vegetation input. The overstory is allowed to remove water from both the upper and lower soil zones, while the understory can only remove water from the upper zones. Solar radiation and wind speed are attenuated through the two canopies based on cover density and leaf area index (LAI). Soil water evaporation is dependant on the climatic demand, modulated by the soil's ability to supply water (Wigmosta et al., 1994). In the case that the snowpack is present, it is assumed to cover the complete grid cell; consequently, no evapotranspiration from the soil or understory layer is calculated when snow cover is present in any grid cell. DHSVM also account for a wet and dry fraction in the vegetative layers which enables the model to account explicitly for interception, storage, and through fall.

Separate shortwave and longwave radiation budgets are developed for both for the vegetation overstory and understory. The overstory receives direct solar radiation (shortwave) and exchange longwave radiation with both the sky and the understory or soil. The understory below an existing overstory also receives attenuated shortwave radiation and exposed understory receives direct shortwave radiation. Finally there is also exchange of longwave radiation between the understory and the ground. Shortwave incoming radiation (beam and diffuse) and diffuse longwave radiation from the sky are supplied to the model (Wigmosta, 2002).

2.1.2 Two-Layer Ground Snowpack Model.

DHSVM models the processes of accumulation and melt of the snowpack using the two –layer, energy- and mass-balance described by Storck and Lettenmaier (1999) and Storck (2000). The model also accounts for energy exchanges taking place between the atmosphere, overstory canopy, and main snowpack. The energy balance components of the model solves snowmelt, refreezing, and changes in snowpack heat content, whereas the mass-balance equations solve the snow accumulation and ablation processes, transformations in the snow water equivalent, and snowpack water yield (Wigmosta, 2002). The model also estimates the changing snow surface albedo, based on the number of days since the last new snow (Laramie and Schaake, 1972).

2.1.3 Canopy Snow Interception and Release

DHSVM models canopy snow processes utilizing a one-layer mass and energy balance model (Storck and Lettenmaier, 1999; Storck, 2000). This snowpack model explicitly represent the topographic and vegetative influences on the energy and mass exchanges that occur on the snow surface, particularly the processes governing snow interception, sublimation, mass release, and melt from a forest canopy. Atmospheric precipitation is partitioned into rain and snow based on atmospheric temperature thresholds on the grid cell and time step, the user defines minimum and maximum temperatures for rain and snow occurrence. The volume of intercepted snow is determined by the efficiency of the process, which is dependant of the leaf area ratio and temperature. This formulation is based on field observations by Storck (2000).

2.1.4 Unsaturated Soil Moisture Movement

Unsaturated moisture movement is simulated using a multi-layer representation based on the two layer model described by Wigmosta et al. (1994). Each soil surface cell may remove water by way of the mechanisms of throughfall, snowmelt, or surface runoff from adjacent cells. The user defines the maximum infiltration rate which is used by the model to calculate infiltration into the upper soil layer. If there is water in excess of the infiltration capacity this is then managed by the surface routing components of the model. When water has infiltrated into the unsaturated soil profile it is able to percolate through the additional layers. This process is controlled using Darcy's Law and the Brooks-Corey relationship (Brooks and Corey, 1964).

Infiltrated water may be removed from the unsaturated profile through : ET from the upper soil layer; transpiration is also possible from inside the soil profile depending on the total percent of plant roots in a soil layer;and lastly, desorption from the top soil layer may occur and is calculated based on the work of Eagleson (1978).

2.1.5 Saturated Subsurface Flow

DHSVM employs both a kinematic and a diffusion approach to route saturated subsurface flow downslope cell by cell. The kinematic method uses slopes to approximate the hydraulic gradient for those cells representing steep areas with thin, permeable soils. However, for areas of low vertical relief, the diffusion assumption is utilized to approximate hydraulic gradients using local water table slopes (Wigmosta et al., 2002).

Subsurface water moving downslope to a channel may be intercepted by a road segment. In the case of the road segment, interception occurs when a road cut depth exceeds the depth to the water table. Channel interception occurs similarly.

2.1.6 Overland Flow

Generation of runoff flow occurs when at least one of three physical conditions is met. First, overland flow occurs when the sum of throughfall and snowmelt exceeds the user-defined infiltration capacity. Second, runoff may also be generated if throughfall or snowmelt occurs on a cell with fully saturated soil layer. Finally, runoff is also possible if the water table rising above the soil surface. (Wigmosta et al., 2002).

Runoff is routed on a cell-by-cell basis downslope in a similar way to subsurface routing. Basically, the overland flow algorithms account for cell size, the volume of the surface water, and the amount of water leaving the system via culvert outflow. The model uses a constant water velocity (Wigmosta et al., 2002).

2.1.7 Channel Flow

Water enters the channel network via subsurface contributions of lateral inflow, direct delivery by way of overland flow or culvert outflow from a road channel. Flow through the network of road ditches and stream channels is routed using a cascade of linear channel reservoirs. Each channel segment represented in the model has uniform hydraulic properties. The user is able to assign hydraulic properties to individual road or stream classes, including length, width, depth, roughness, and channel slope during the preprocessing of the road and stream. These constants assign a constant flow velocity per channel segment and time step that is calculated from Manning's equation (Wigmosta et al., 2002).

2.1.8 Water Temperature

The stream temperature component of DHSVM calculates a radiative energy balance in each channel segment at each time step. Additionally the flux of heat associated with the flow in water into and out of each segment is accounted for. The model is based on the radiative heat balance model described by Chapra (1997). The model makes use of the existing gridded metrological forcing information and requires only a few calibration parameters in the configuration file and an additional stream class property (the mixing ratio) in the stream-class.dat file.

$$\frac{dT_s}{dt} = \frac{Q}{V}T_{in} + \frac{J_{DS}}{\rho C_p H} + \frac{J_{AL}}{\rho C_p H} - \frac{Q}{V}T_{Out} - \frac{J_{WL}}{\rho C_p H} - \frac{J_{COND}}{\rho C_p H} - \frac{J_{EVAP}}{\rho C_p H}$$

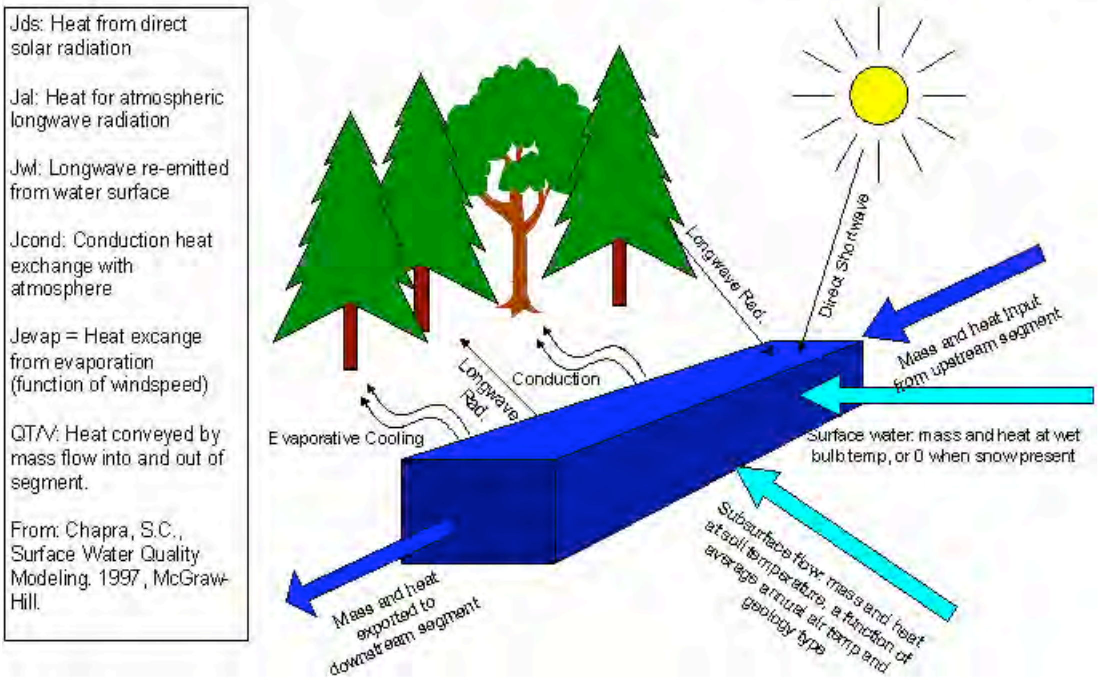

Figure 1 Stream Temperature Heat Balance Equation

2.2 Preprocessing

There is a basic progression of preprocessing steps completed for each of the basins. Implementation of DHSVM in these basins basically involves GIS preprocessing of the necessary spatial inputs, collection and formatting of meteorological drivers, formatting the necessary configuration files. Figure 2 summarizes the sequence of preprocessing steps.

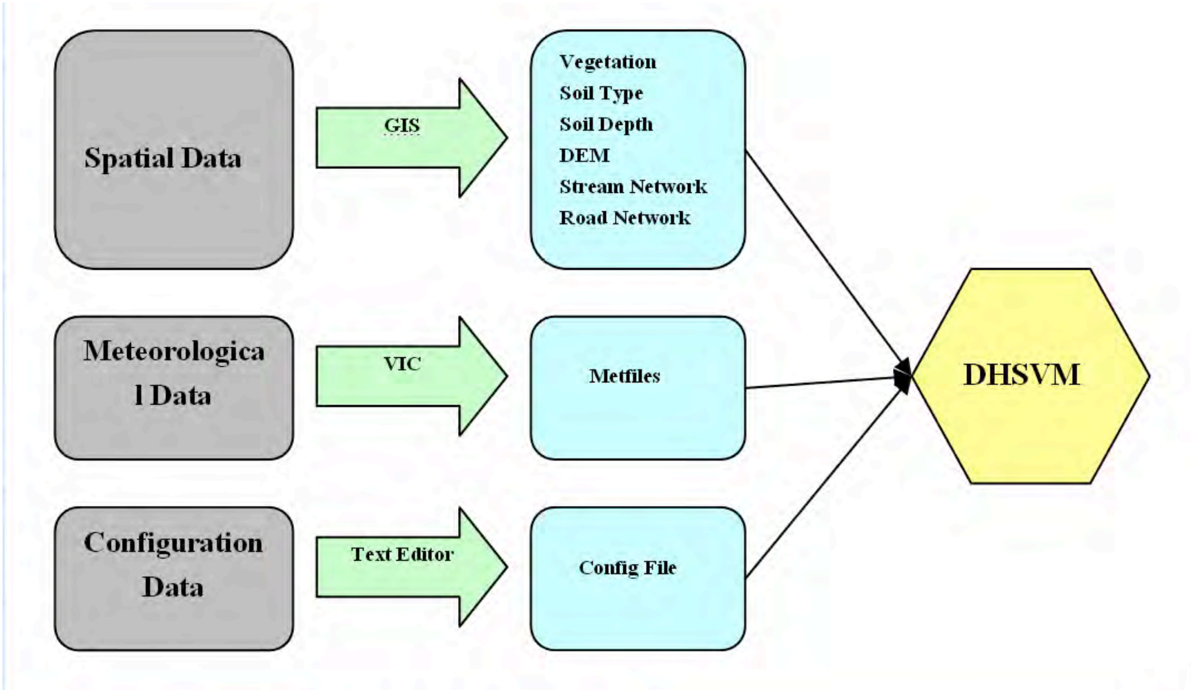

Figure 2 Preprocessing schematic diagram. This figure illustrates the three preprocessing steps needed to implement the model for a location.

2.2.1 GIS Preprocessing

While DHSVM is not directly linked to any particular Geographical Information System (GIS), the inputs and outputs are best managed within ArcGIS from ESRI. Spatial data was obtained from diverse sources and compiled, edited, and formatted using ArcGIS 9.2. The basic inputs to the model are elevations, soil types, vegetation types, road network and stream network. From this spatial information it is possible to generate the following inputs: soil depth, terrain shadowing and percent of open sky.

2.2.1.1 Raster Data

Seamless 30-m and 90-m resolution digital elevation models were obtained for each watershed from the National Elevation Dataset (United States Geological Survey, National Map Seamless Server, 2009). Since the model is unable to handle sinks in the topography the input Digital Elevation Model (DEM) was reconditioned in ArcInfo in order to produce a depressionless model for hydrologic simulations. This reconditioning is an ArcHydro process that ensures a linear drainage pattern onto the model grid. This is done through two basic methods: 1) filling in sinks in the drainage area by raising the elevations of those grid cells, and 2) lowering the elevation of the cells corresponding with the vector drainage network, efficiently burning the channel network into the DEM. Refer to Figure 3 for an example DEM input file.

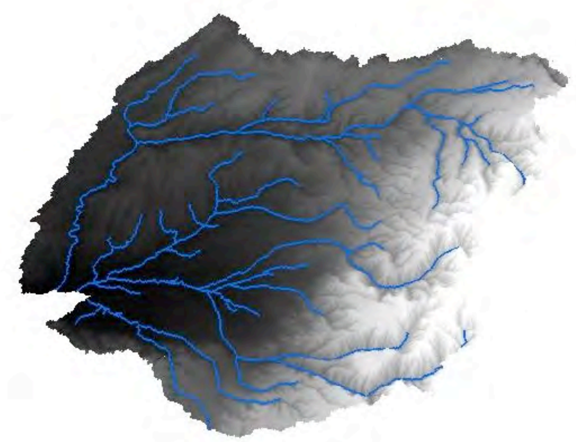

Figure 3 Example of a watershed DEM input file.

Soils spatial data were obtained online from the United States Department of Agriculture Natural Resources Conservation Service (USDA NRCS). The datasets used is the Soil Survey Geographic Database (SSURGO; Soil Survey Staff, 2006). The SSURGO data provide soil information at a scale of 1:24,000.

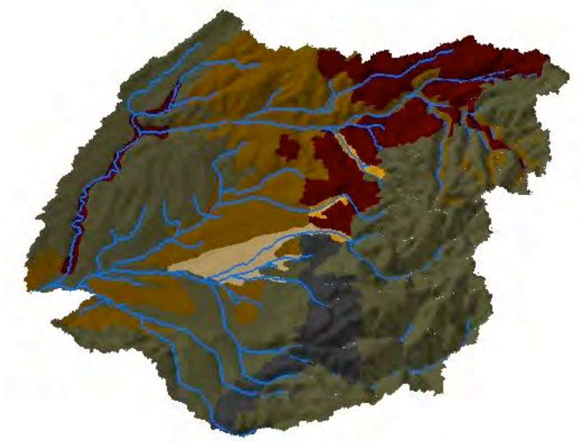

Figure 4 Example of a watershed soil input file.

A soil depth grid is also needed by the model. The depth of the soil profile corresponding to specific soil types is generally known information; however, this is not an available spatial data layer. DHSVM incorporate an ARCinfo script that generates a soil depth grid in ArcInfo for input into the model. This raster is created as a function of the watershed slope and a range of soil profile depths based on the soil type.

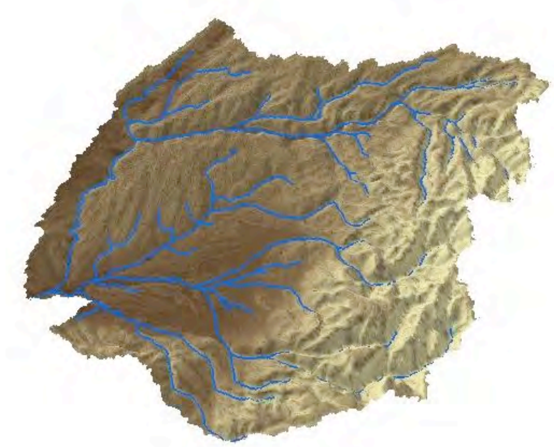

Figure 5 Example of a watershed soil depth input file.

Vegetation cover data at 30-m resolution were obtained online from National Land cover Database (NLD) datasets (2001). These data were derived using Landsat TM-

7 imagery to classify the vegetative cover. The level of detail provided by NLD is not necessarily appropriate for DHSVM input, particularly because the data to accurately describe the differences in the physical parameters of some vegetation types is not available. Due to this fact, the vegetation grid was reclassified into less classes utilizing ArcMap.

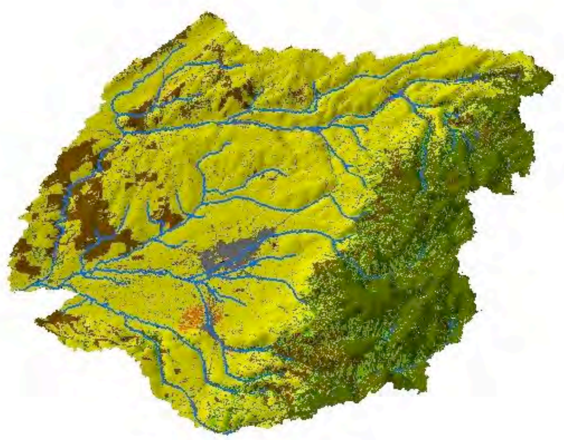

Figure 6 Example of a watershed vegetation input file.

The model ensures that every pixel from the inputs is associated with a grid cell in the watershed. To effectively accomplish this process DHSVM uses a mask of the watershed area to select only those cells within the watershed boundary for analysis. This process ensures that the limits of the area of interest are the same for every spatial elevation, soil type, soil depth, and vegetation type file. This mask raster is created using the ArcHydro 1.3 Batch Watershed Delineation Tool. By working through a series of terrain preprocessing steps, each pixel in a DEM is assigned a flow direction. ArcHydro can then delineate a watershed polygon from any point specified within the raster by selecting all pixels that collectively drain to that point. After this the ArcToolbox Feature to Raster Tool was then used to convert this polygon feature class to a 30-m resolution grid. Ultimately, this mask raster of the watershed was used in the model to extract the drainage basin values from the soil type, soil depth, vegetation type, and DEM raster inputs.

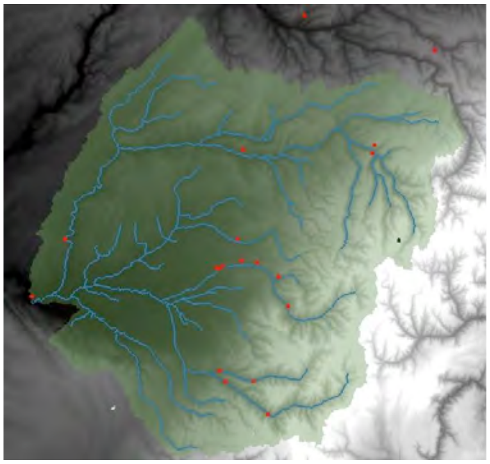

Figure 7 Example of a watershed mask input file.

2.2.1.2 Vector Data

DHSVM requires roads and stream networks within the watershed extent. Digital spatial data of the road network was found at University of Washington WAGDA. Stream network data were obtained through the Washington State Department of Ecology Geographic Information System web site. However, these hydrology data is only used as a digital layer for mapping purposes, locations and identity of named stream reaches. These data is not used as the stream coverage for input into DHSVM since the generation of a continuous stream network with assigned flow direction per segment is a required preprocessing step in the model.

The STREAMNETWORK Arcinfo scrip creates a stream network with streamflow topology based on the reconditioned DEM, the watershed of interest previously delimitated, and a stream initiation threshold defined by an area in m^2.

The contributing watershed area parameter for stream initiation recommend by Storck et al. (1998) is a minimum surface of 20000 m^2 for small catchments on the west slopes of the Cascades Range in Washington State. On the drier east side of the Cascades Doten and Lettenmaier (2004) used a stream initiation area of 40000 m^2.

The road system definitions file is created in a similar way using ROADNETWORK scrip in ArcInfo.

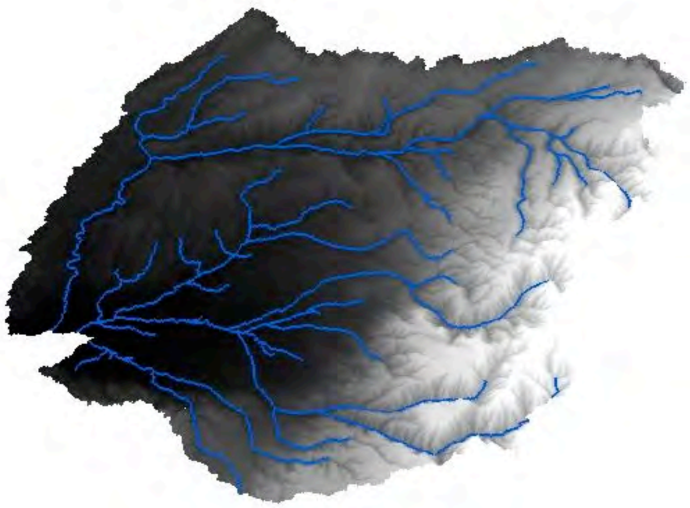

Figure 8 Example of a watershed stream network map.

2.2.2 Meteorological Data

DHSVM is able to work using meteorological records associated with different weather stations. The model distributes weather parameters within the watershed modeled, for each time step, using an interpolation method. The model requires the following meteorological data files for each time step and weather station defined: air temperature (°C), wind speed (m/s), relative humidity (%), incoming shortwave radiation (W/m2), incoming longwave radiation (W/m2), and precipitation (m/time step).However, the existing network of meteorological observing stations in the US does not afford the type of spatial and temporal coverage necessary to drive this micro scale models in some of the basins of interest. When this situation is encountered it is often necessary to use a gridded product that is derived statistically from the observing network of meteorological stations. The gridded product has already gone through a series of quality control processing steps which makes it easier to get ‘model ready’. Also, these products are more conducive to the downscaling approaches used to derive local data from the global circulation models (GCM) used in conducting climate change experiments.

There exists a 1/16th gridded data set maintained by the University of Washington that covers the PNW and Canada. This data set was derived by Deems et al using the methods of Hamlet and Lettenmaier (2005). This data set contains precipitation, Tmax , T min and wind speed at daily intervals. Since this parameters are not enough to run DHSVM, the Variable Infiltration Capacity model (VIC) must be ran for each cell to obtain relative humidity (%), incoming shortwave radiation (W/m2), incoming longwave radiation (W/m2), and precipitation (mm/time step). This process also is able to reduce the time scale from daily to 3 hours time steps required by DHSVM. Once these output files of VIC are available it is still necessary to process them to obtain wind speed at the same height required by DHSVM. In order to produce these data a procedure defined by Arya (1998) to scale the wind must be applied.

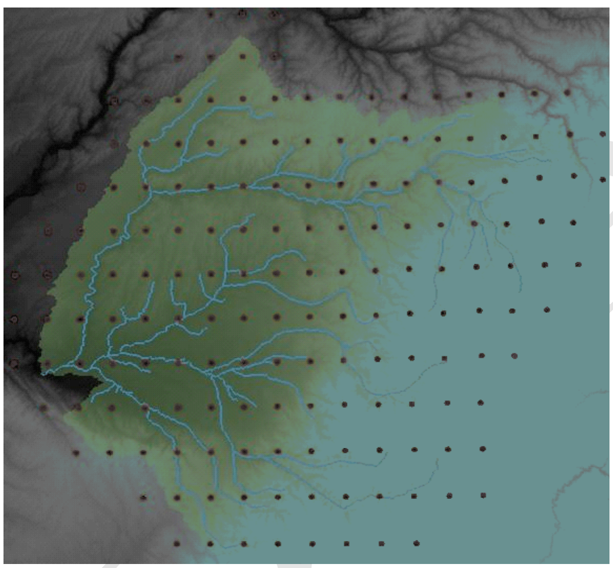

Figure 9 Example of a watershed gridded meteorological station input file.

2.2.3 Configuration File.

DHSVM requires an ASCII configuration file that serves as a reference table for the values describing the physical conditions of the basin. The configuration file allows the model to interpret the thematic spatial inputs, and therefore, is generally where modifications are made to change the outputs. DHSVM is capable of model any number of soil or vegetation types in a watershed. Complementary, each of the vegetation type may consist of two individual vegetative layers, and each soil type may be composed of many soil layers. The inventory of physical values necessary to describe each individual soil and vegetation layer is extensive. Furthermore, many of the parameters used in model calculations are obscure and are not readily available in the literature for each unique soil and vegetation type. Thorough completion of the configuration file using cited values for soil and vegetation parameters was time-intensive. Some generalization was necessary; however, the goal in this case was to parameterize the model for the calibration run using the best available referenced values.

2.3 Case Study Watersheds

DHSVM was applied to the following sub basins of the Columbia River: Upper Yakima, Naches, Methow , West Kettle and Walla Walla.

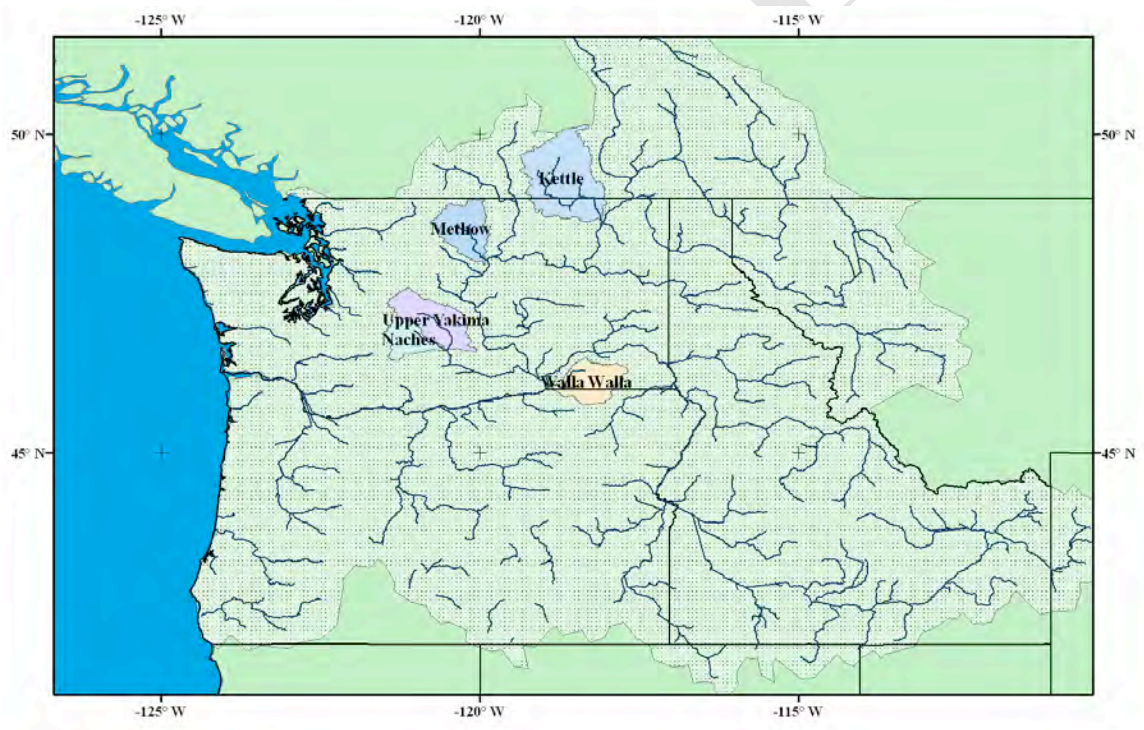

Figure 10 Location of the sub basins analyzed.

2.3.1 Upper Yakima

The Upper Yakima River is a tributary of the Yakima River in south central and eastern Washington State. The river rises in the Cascade Range at Keechelus Dam on Keechelus Lake near Snoqualmie Pass, northwest of Cle Elum. Main characteristics of this watershed are summarized in Table 1. Vegetation types within this watershed are summarized in Table 2. Soil types within this watershed are summarized in Table 3.

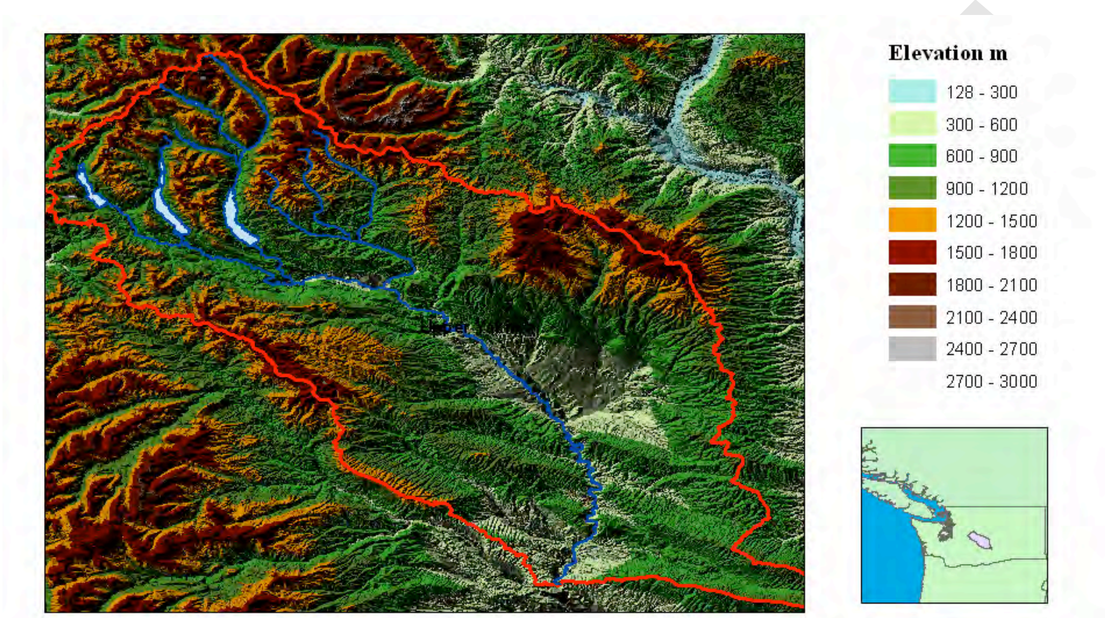

Figure 11 Location of the Upper Yakima basin.

2.3.2 Naches

The Naches River is a tributary of the Yakima River in central Washington. Beginning as the Little Naches River, it is about 75 miles long.[1] After the confluence of the Little Naches and Bumping River the name becomes simply the Naches River. The Naches and its tributaries drain a portion of the eastern side of the Cascade Range, east of Mount Rainier and northeast of Mount Adams. In its upper reaches, the Naches River basin includes rugged mountains and wildernesses. The lower Naches River and its tributary the Tieton River flow through valleys with towns and irrigated orchards northwest of Yakima, where the Naches River joins the Yakima River.

Main characteristics of this watershed are summarized in Table 1. Vegetation types within this watershed are summarized in Table 2. Soil types within this watershed are summarized in Table 3.

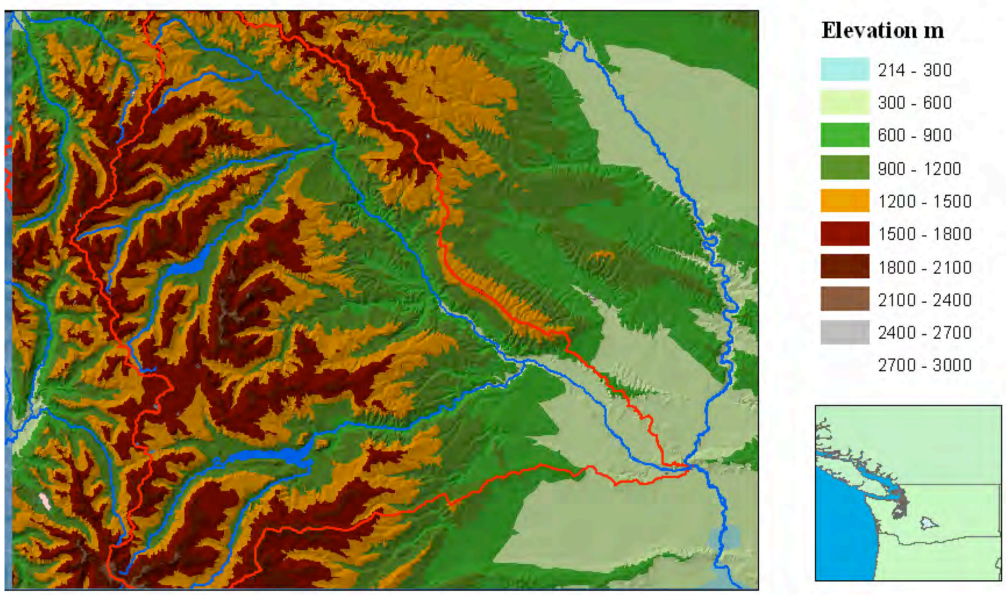

Figure 12 Location of the Naches basin.

2.3.3 Walla Walla

The Walla Walla River is a tributary of the Columbia River, joining the Columbia just above Wallula Gap in the southeastern of Washington State. The river flows through Umatilla County, Oregon and Walla Walla County, Washington. The headwaters of the Walla Walla River lie in the Blue Mountains of northeastern Oregon. The river originates as the North and South Forks of the Walla Walla River.

Main characteristics of this watershed are summarized in Table 1. Vegetation types within this watershed are summarized in Table 2. Soil types within this watershed are summarized in Table 3.

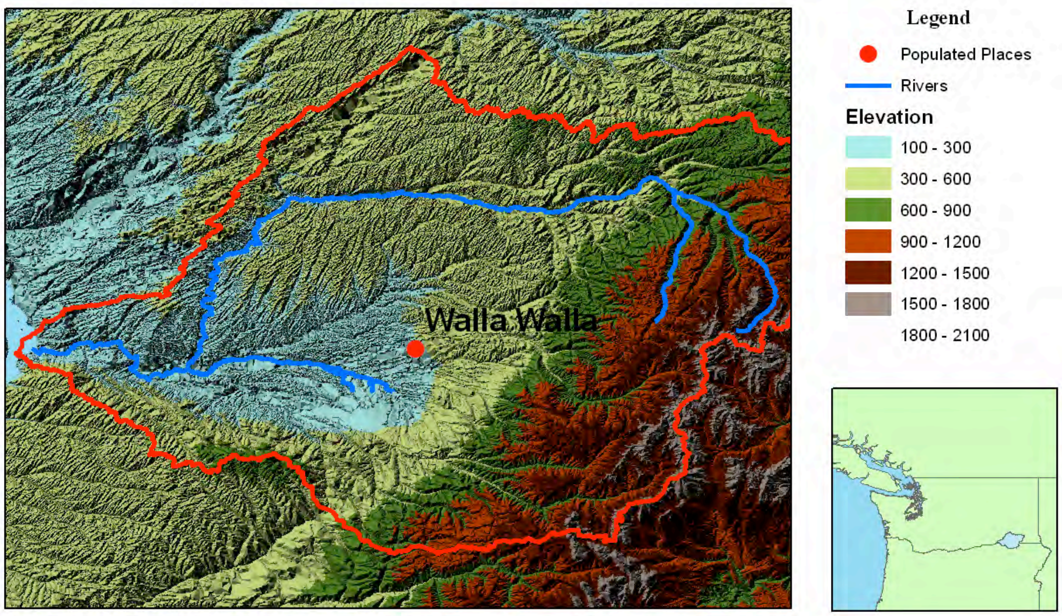

Figure 13 Location of the Walla Walla basin

2.3.4 Methow

The Methow River is a tributary of the Columbia River in northern Washington State. The Methow River, along with its tributaries the Twisp River, Cedar Creek, and Early Winters Creek, originates in a cluster of high mountains such as Golden Horn, Tower Mountain, Cutthroat Peak, Snagtooth Ridge, Kangaroo Ridge, Early Winter Spires, and Liberty Bell.

Main characteristics of this watershed are summarized in Table 1. Vegetation types within this watershed are summarized in Table 2. Soil types within this watershed are summarized in Table 3.

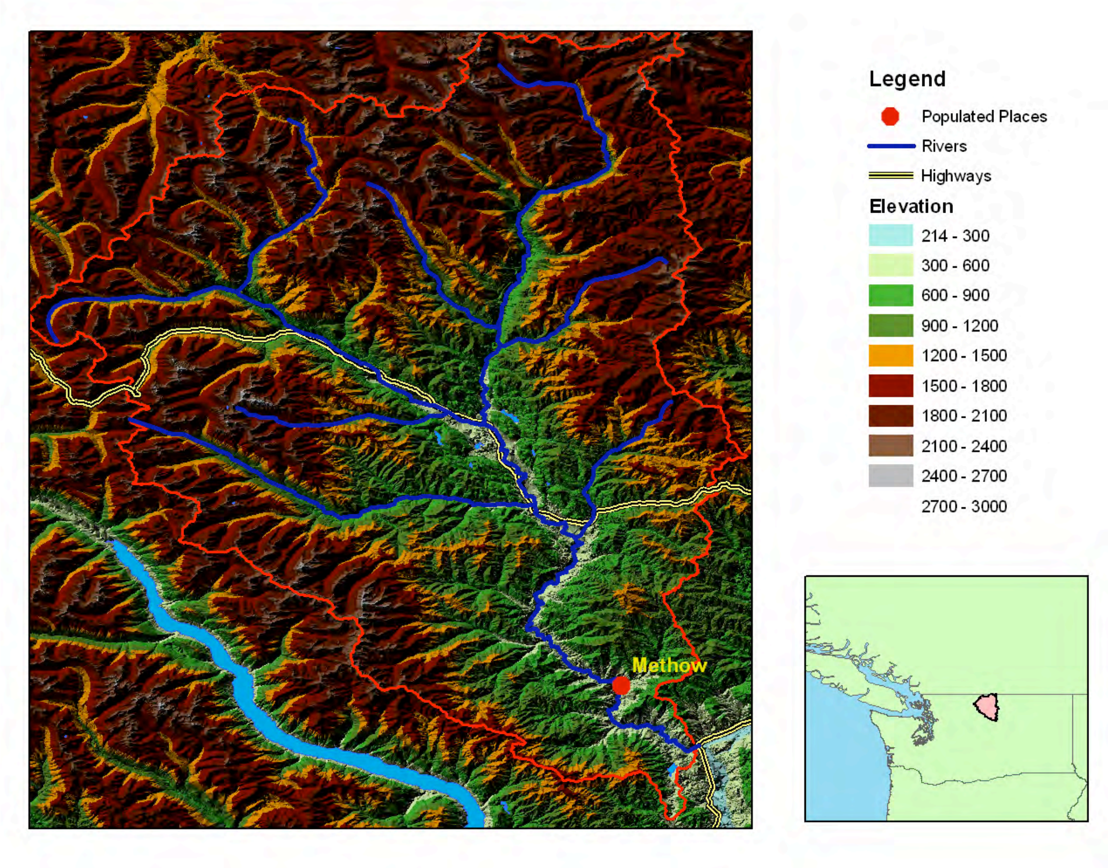

Figure 14 Location of the Methow basin

2.3.5 West Kettle

The West Kettle River is a tributary of the Kettle River in South British Columbia. The Kettle River is a tributary of the Columbia River, joining it near Kettle Falls, Washington. The Columbia River at this point is a large reservoir called Lake Roosevelt.

Main characteristics of this watershed are summarized in Table 1. Vegetation types within this watershed are summarized in Table 2. Soil types within this watershed are summarized in Table 3.

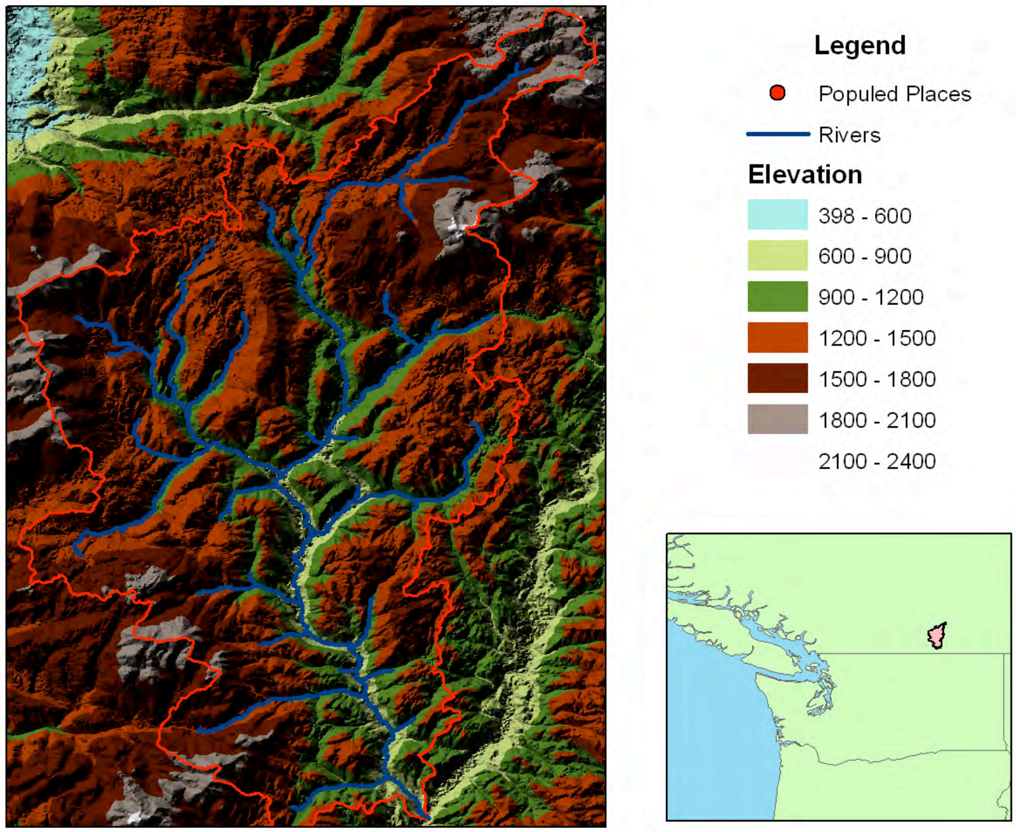

Figure 15 Location of the West Kettle basin

Table 1 Main characteristic of case study watersheds.

	Upper Yakima Basin	Naches Basin	Walla Walla Basin		Methow Basin	Upper Kettle Basin
			Blue Mtns	Lowlands		
Drainage Area (sq. km.)	4144	2875	4293		4620	1870
Maximum Elevation (m)	2388	2496	1905	270	2674	2307
Minimum Elevation (m)	414	329		80	284	626

Table 2 Vegetation types of within case study watersheds. Grey boxes indicate that these vegetation types are absent from basins.

Vegetation Type	Upper Yakima Basin	Naches Basin	Walla Walla Basin	Methow Basin	Upper Kettle Basin
Evergreen Needleleaf	52%	72%	19%	60%	
Open Shrub	27%	17%	12%	23%	
Grassland	11%	4%	1%	11%	
Cropland	6%	4%	56%		

Urban			4%		
Closed Shrub			6%		
Bare land				4%	

Table 3 Soil types within case study watersheds. Grey boxes indicate that these soil types absent from basins.

Soil Type	Upper Yakima Basin	Naches Basin	Walla Walla Basin	Methow Basin	Upper Kettle Basin
Sandy Loam	36%	19%	23%	25%	
Loam	37%	50%	5%	27%	
Silty Loam	16%	19%	54%	47%	
Bedrock	5%				
Sandy			23%		
Sand			2%		

2.4 Model Calibration

Calibration techniques for the Distributed Hydrology Soil Vegetation Model (DHSVM) are dependent on the information available during the implementation. Whitaker et al (2003), defined a three step approach to calibrate a basin. First adjust parameters dealing with snow melt and accumulation in non-forested areas, then with parameters affecting melt and accumulation below the canopy and then finally with soil parameters affecting runoff generation. The calibration of soil parameters is discussed by Storck et al. (1998) he utilized parameters such as depth of the rooting soil layers, depth of soil below the rooting zones and lateral saturated hydraulic conductivity to obtain a calibration to observed basin outflow hydrographs

A normal approach in DHSVM is adjusting precipitation by a factor proportional to the discharge of the basin. The strategy consists in multiply or scale precipitation within the basin to obtain a fixed factor between it and the annual discharge. Those factors are empiric numbers based on observation in basin with the same conditions. Wigmosta et al. (1994) indicated that the model was calibrated to annual discharge by multiplying the elevation corrected precipitation by an additional 16%. A similar strategy was also employed by Stock et al. (1998) in the PNW, Palmer and Hahn (2002) in Oregon and by Whitaker et al. (2003) in a small catchment in B.C. . This correction factor has been utilized as high as an additional 20% (Linsley et al., 1982; Legates & DeLiberty, 1993, Palmer & Hahn, 2002).

Despite the fact of this normal approach to Calibrate DHSVM it was not utilized in these implementations. This was done as a way to maintain consistency between the meteorological inputs of VIC and DHSVM. Since the models were implemented utilizing all the gridded met files available for the basins is not possible to utilize temperature lapses as a calibration tool. Therefore soil, geological and vegetation parameters were adjust to obtain the proper monthly and annual discharge.

Table 4 Summary error statistics for DHSVM calibration for 5 case study watersheds

Basins (gage)	Annual mean			N-S model efficiency		
	Nat. (cms)	Sim. (cms)	Rel. error (%)	Calib. (daily)	Calib. (monthly)	Valid. (monthly)

Kettle River at Westbridge

Calibration period (1986-2000)

Validation period (1971-1985)

2.5 Model Results

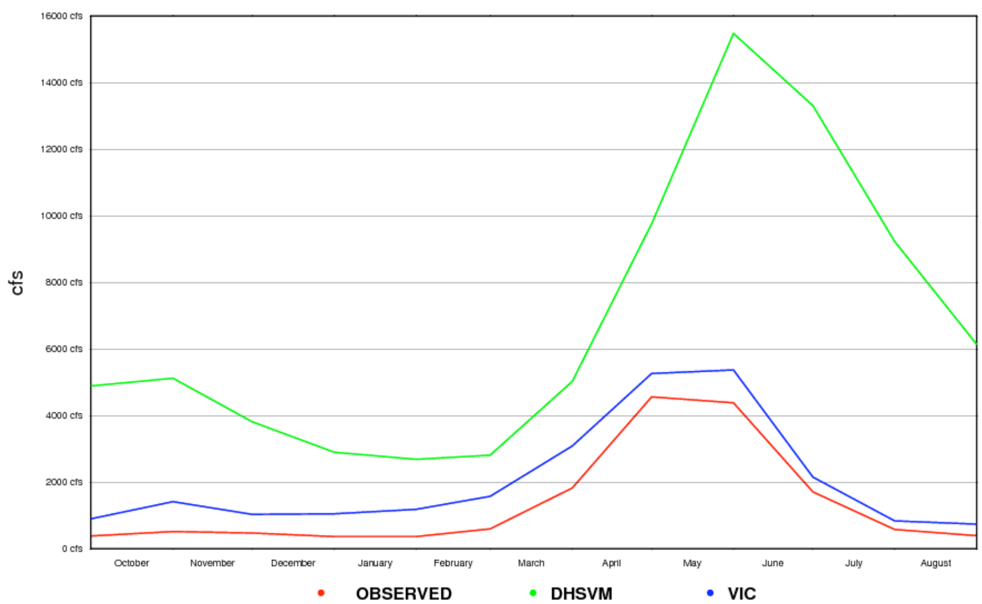

Figure 16 Methow River Hydrograph at Pateros

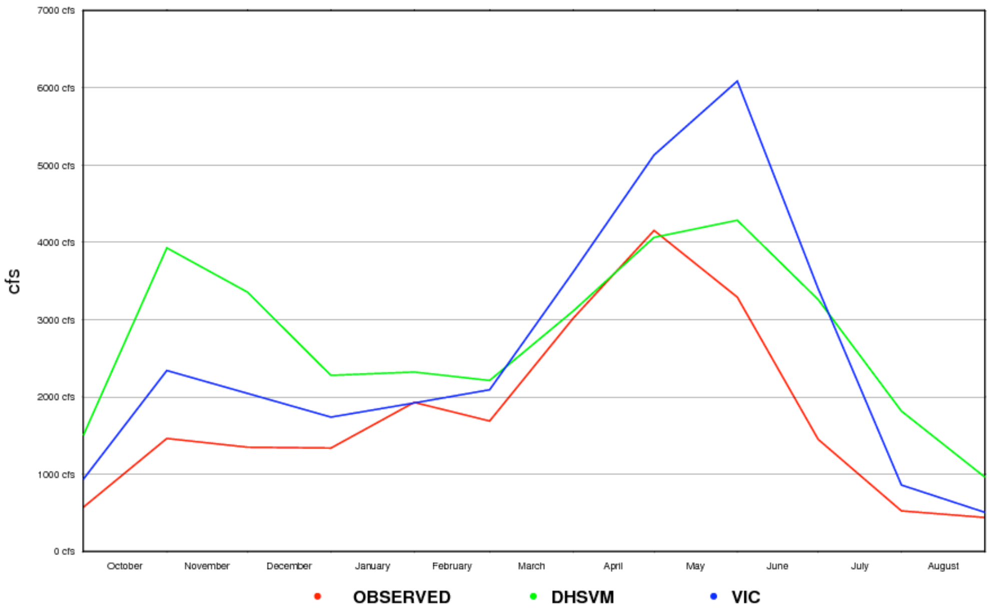

Figure 17 Naches River Hydrograph at Yakima

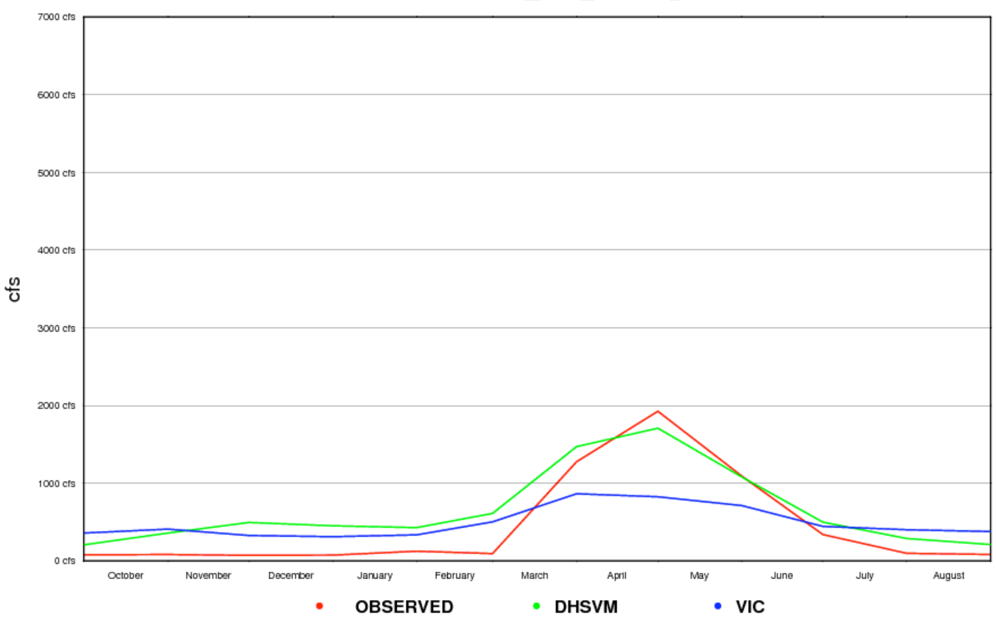

Figure 18 West Kettle River Hydrograph at West Bridge

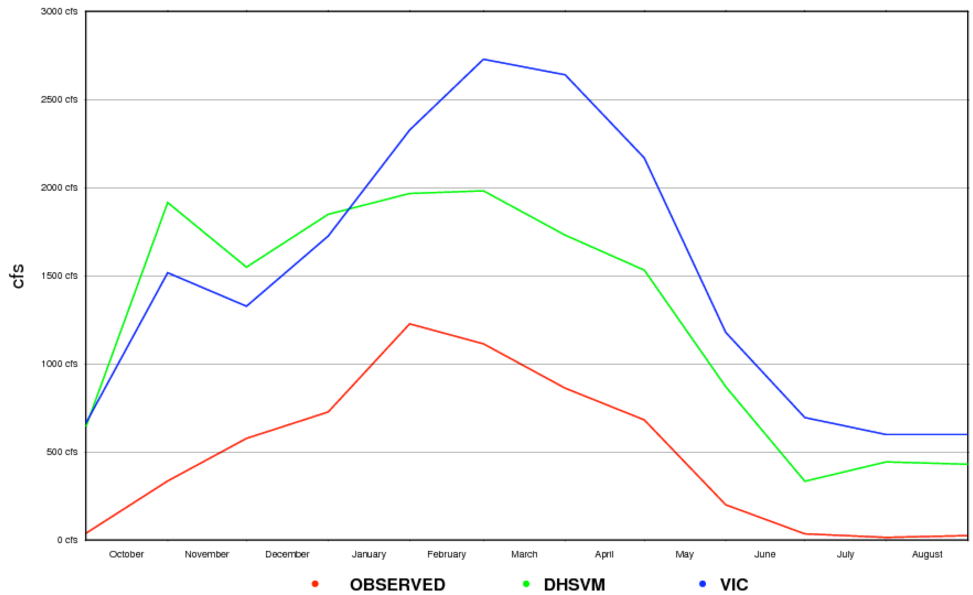

Figure 19 Walla Walla River Hydrograph at Touchet

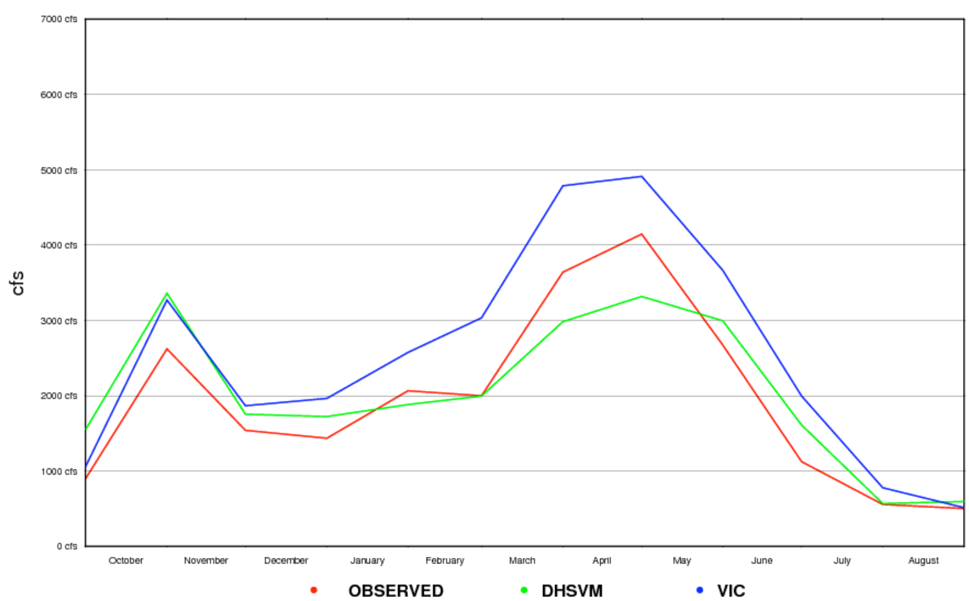

Figure 20 Upper Yakima River Hydrograph at Cle Elum

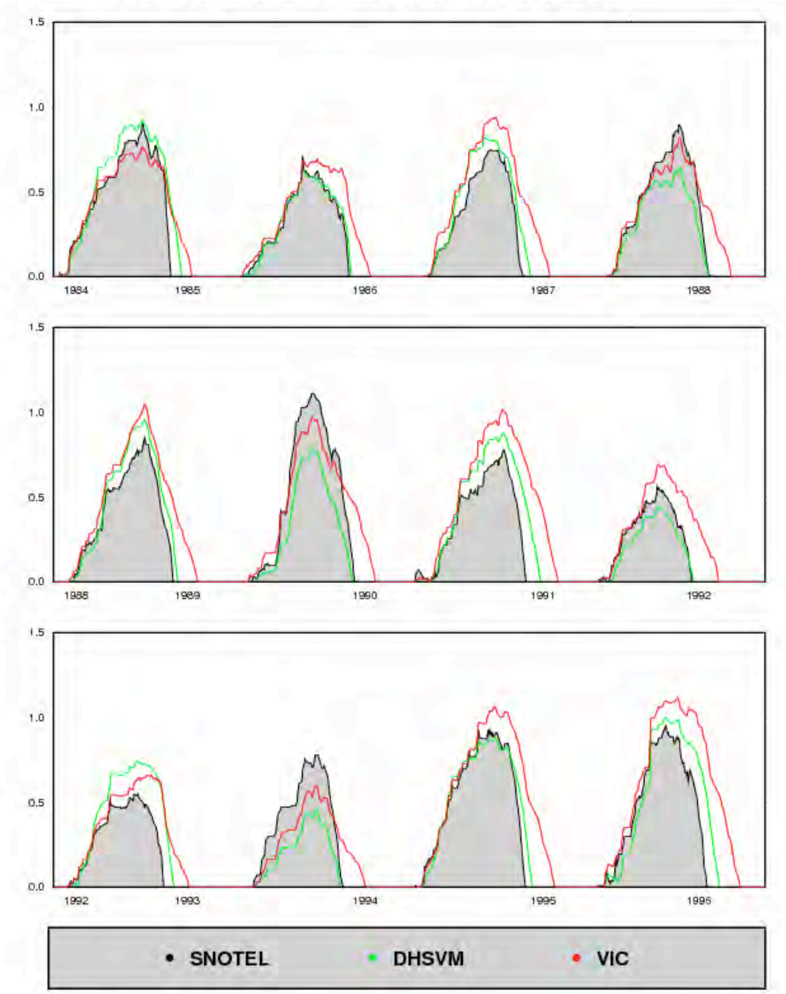

Figure 21 Snow Water Equivalent Comparison at Fish Lake SNOTEL Station

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ANALYSIS OF EXTREME EVENTS

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1. Introduction

The performance of water resources systems is often most sensitive to changes in hydrologic extremes rather than changes in mean conditions. Currently the rising demands on the Columbia River associated with irrigation withdrawals, instream requirements for fish, and hydropower production aggravate the risks associated with low flow events (such as those occurring in water year 2001). Similarly, high flow risks create hazards for built infrastructure and human systems (Hamlet and Lettenmaier 2007) and for natural habitat ecosystems (Mantua et al. 2009).

The implications of changing hydrologic extremes in the Pacific Northwest (PNW) due to climate change in the 21st century are extensive and include hydropower production (Hamlet and Lettenmair 1999), flood control operations (Lee et al. 2009) instream flow for fish passage (Hamlet et al. 2009), and local-scale impacts to instream habitat for fish (Battin et al. 2008; Crozier et al. 2008; Mantua et al. 2009). Thus water resources planning requires quantitative information on changing extreme high or low flows resulting from climate change. In response to this need, this study examines changes in extreme flow statistics in a large number of PNW basins of varying size through an analysis of simulated streamflows for the historical past and for a range of 21st century climate change scenarios associated with the fourth report by the Intergovernmental Panel on Climate Change (IPCC AR4, Chapter 10).

The distinct topography that characterizes the Pacific Northwest (PNW) interacts with atmospheric patterns from the Pacific Ocean to orchestrate the region's climate, and the hydrologic characteristics of rivers. Four major mountain chains carve the landscape of the PNW: the Coast Range in western Oregon, the Olympics in western Washington, the Cascade Range extending from southern Oregon to southern British Columbia and the Rocky Mountains stretching along the eastern limits of the PNW. The region's unique topographic and climatic features give rise to a diverse system of watersheds, dominated by the larger Columbia and Snake River basins on the eastern side of the Cascade Range and various smaller coastal drainages on the western side of the Coast and Cascade Ranges. The Cascade Range broadly delineates two climatic regions in the PNW: continental in the east and maritime in the west. The region east of the Cascades is characterized by a wider range of seasonal temperatures, typically hot in the summers and cold in the winters. Some areas of this region receive an average annual precipitation of only about 250 mm, with greater snow accumulation at lower elevations than on the west side of the Cascades. Annually, the relatively wet west side of the Cascade Range receives approximately 750 mm of precipitation, with greater precipitation at higher elevations (> 2500 mm) falling as a mix of rain or snow depending on winter temperatures. During the period of October through March the Pacific storm track delivers most of the precipitation in the PNW as rain at warmer, lower elevations or as snow at cooler, higher elevations. The winter precipitation and temperature regimes in the PNW determine both the amount and the timing of flow in the rivers, so shifts in climate alter both streamflow magnitude and timing. Figure 1 shows hydrographs exemplifying the annual streamflow behavior for the three characteristic basins in the PNW as described in Hamlet et al (2005). Regional warming tends to shift snowmelt dominant and transient snow basins towards more rain dominant behavior, increasing winter flows and decreasing summer flows (Mantua et al. 2009; Elsner et al. 2009; Chapter 5, this report).

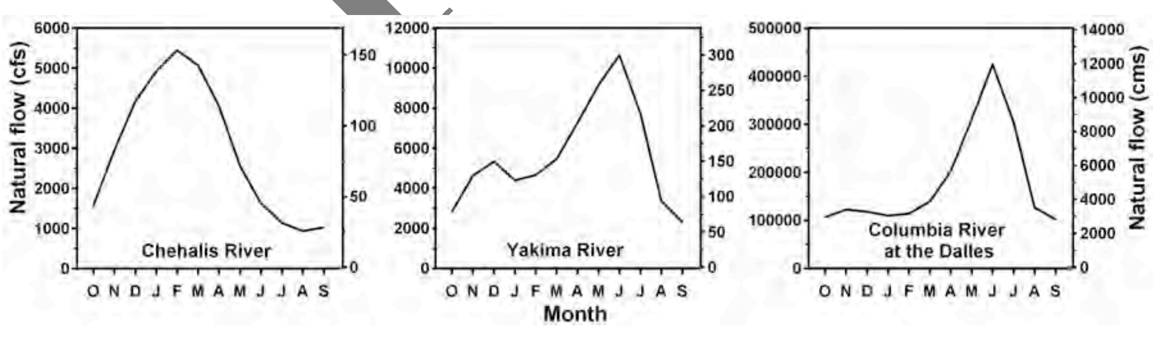

Figure 1: Simulated streamflow hydrographs for three typical basins in the PNW: a) rain dominant, b) transient snow, c) snowmelt dominant.

Mote et al. (2005), Hamlet et al. (2005, 2007) and Hamlet and Lettenmaier (2007) demonstrated that average winter temperatures for each basin can be used to characterize the behavior of individual basins since wintertime temperature regimes largely govern the primary mechanisms that produce streamflow. Mote et al. (2005) and Hamlet et al. (2005) showed that losses of snowpack in the Western U.S. were strongly dependent on mid-winter temperature regimes, and Hamlet et al. (2007) and Mantua et al. (2009) showed that changes in flood risk could be broadly attributed to mid-winter temperatures in each river basin.

In this report, following methods developed by Hamlet et al. (2007) and Mantua et al. (2009) we assess changes in extreme streamflow statistics at 297 locations (Chapter 8, this report) using daily streamflow projections for future scenarios. Projections of temperature (T) and precipitation (P) from regionally downscaled Global Climate Models (GCMs) drive the hydrological models used to produce the streamflows at a daily time step (Chapter 5, this report). The two regional downscaling approaches used in these analyses, the "composite delta" and "hybrid delta" methods, are described by Hamlet, (Chapter 4, this report).

2. Approach/Methods

2.1. VIC model output

The hydrologic model, Variable Infiltration Capacity (VIC), implemented at the spatial resolution of 1/16th degree latitude and longitude, generated the daily runoff and base flows used to calculate daily streamflow for this study (see Elsner et al. this study, Hamlet 2005). To drive the VIC model, a historical (1915-2006) input dataset, including the variables of daily precipitation, maximum and minimum daily temperatures and windspeed, was developed as described in Chapter 3 (this report). The IPCC AR4 report (2007) archived datasets from Global Climate Models (GCMs) under numerous greenhouse gas (GHG) emissions scenarios. To calculate future streamflows for this report, the VIC model processed input datasets of future conditions derived from two methods of downscaling GCMs into regional datasets under two emissions scenarios. The first downscaling approach uses the delta method, where monthly perturbations are calculated from multi-model means of future conditions and then applied to the historical record (Elsner et al. 2009). Chapter 4 of this report describes the second approach, the hybrid delta method, to statistically downscale 10 GCMs for the A1B (medium) and 9 GCMs for the B1 (low) emissions scenarios. Resulting streamflow scenarios were evaluated for three future time periods: 2020s, 2040s, 2080s, and two emissions scenarios to produce an ensemble of 66 scenarios, 6 for the delta method and 60 for the hybrid delta method. Because there are 20 realizations for each future time period (10 for each GHG scenario), an uncertainty analysis of the change in streamflow statistics is straightforward to produce. For example, the uncertainty in the future flood magnitude can be approximated by comparing the range of the estimates projected for a given return frequency from the downscaled models..

2.2. Extreme flow statistics & basin classification

Applying the delta and the hybrid delta methods, Elsner et al. (Chapter 5, this study) generated the streamflows used here to calculate extreme flow statistics for four time periods: the historical (1915-2006) and three future intervals (2020s, 2040s, 2080s). The annual maximum streamflow time series for each time period and basin were ranked and fitted to the Generalized Extreme Value distribution using the L-moments method (Wang 1997; Hosking and Wallis 1993; Hosking 1990). Flood magnitudes with 20-year, 50-year and 100-year return frequencies were estimated for each basin and time period from the fitted probability distributions. Likewise, the same probability distributions were used to estimate the 7-day consecutive lowest flow with a return frequency of 10-years (7Q10) for each basin and time period. From these we computed the ratio of the magnitudes (historical versus model/scenario/time interval combinations) for each flow statistic.

The air temperature fields of the historical period for each downscaled dataset were used to calculate the average temperatures during the winter months of December, January and February (DJF). The DJF for each basin in this study was estimated to classify individual catchment's winter temperature regime. According to Hamlet et al. (2007) snowmelt dominant basins have a DJF < -6 ^{o}C, the DJF of transient basins is between -6 ^{o}C and 5 ^{o}C, and rain dominant basins have a DJF exceeding 5 ^{o}C. Additionally,following methods outlined by Mantua et al. (2009), the new return frequency for the historical 20-year flood event was also determined for the future projections.. The sensitivity of each basin to increased temperatures was characterized by comparing mid-winter temperature regimes to the change in magnitude of the 20-year return flood event.

3. Key Findings/Discussion

As discussed in Chapter 5 (this report), the Columbia basin shifts towards more rain dominant behavior with regional warming, which creates changes in both flood and low flow statistics that vary with mid-winter temperatures. Figure 2 shows the maps of the shifting characterizations of these basins, measured as the ratio of April 1 snowpack to October-March total precipitation, as time progresses through the 21st century under the A1B and B1 scenarios. The topmost map shows the spatial distribution of basin types for the historical period (1970-1999). Historically, snowmelt dominant basins prevail in the northern PNW, the headwaters of the Columbia River basin, extending south into the east side of Cascades in Washington and the higher elevation basins of the Rockies in Idaho and northern Montana. Transient basins predominate where mid-winter temperatures fluctuate around 0^{o}C at mid-elevations of the Cascades and Rockies, in central Washington and Oregon and in southern and western Idaho. Rain-dominant basins are confined to the coastal stretches in Washington and Oregon, west of the Cascades and Coast ranges, and in large swathes of warmer regions in central and southern Oregon and smaller patches in southeast Washington and southwest Idaho. In later projections for the 21st century, future warming provokes the a progressive shift from snow dominant to transient basins and from transient basins to rain dominant (lower panels of Figure 2). Furthermore, this shift in basin characterization occurs at a faster rate for the A1B than for the B1 scenarios. By the 2080s for the A1B scenario, there is a complete loss of snowmelt dominant basins in the Cascades and the Rockies, and only a few transient basins remain at higher elevations. This shift in basin type has implications for the timing of peak flows since the mechanism driving the flows is changing under warmer conditions.

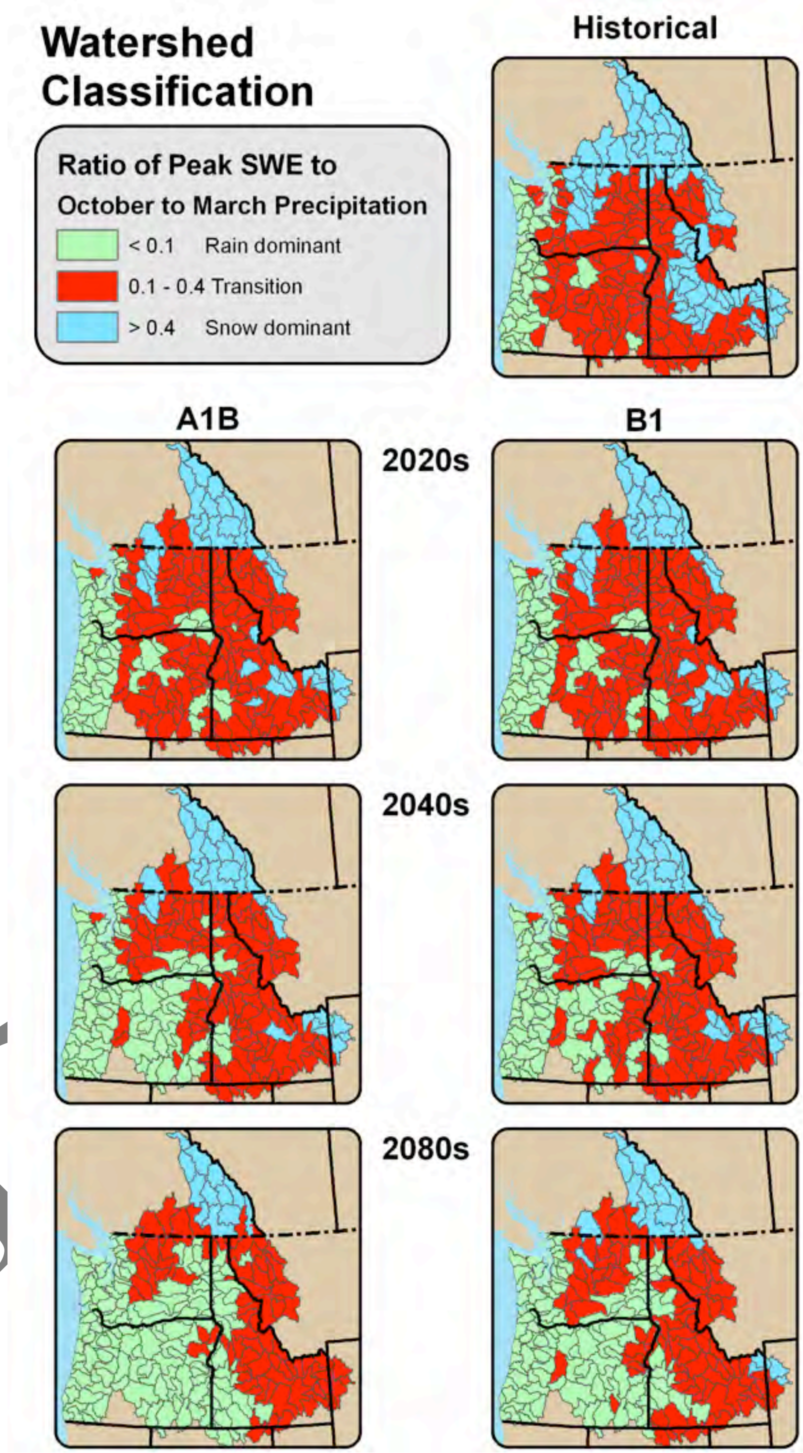

Figure 2: Ratio of April 1 SWE to total March-October precipitation for the historical period (1916-2006), for the A1B scenario (left panel), and for the B1 scenario (right panel) at three future time periods (2020s, 2040s, 2080s).

3.1. Changes in Flood Risk

Maps of the entire PNW indicating flood risk magnitudes are paired with scatterplots characterizing each basin's DJF and the risk of increased flood frequency for the 20-year (Figures 3 and 4) and for the 100-year events (Figures 5 and 6). On the whole, this study indicates that future warming reduces flood risk for snowmelt dominant basins (basins with mid-winter temperatures less than about –6˚ C for this analysis). Peak flows for these basins usually occur in the early summer, when snowmelt contributions are highest with warming spring temperatures. Since the spring snowpack is projected to decline as future temperatures increase (Elsner et al. this report), the overall flood magnitude is expected to decrease for these basins. Spatial patterns for the 20-year and 100-year flood ratio (future/historical) indicate slight or no increases in flood risk for basins typified by snowmelt dominance, as in the interior and upper Columbia basin and the higher elevation watersheds in the Rocky Mountains (Figures 3 and 5, respectively). Related Figures 4 and 6 show scatterplots of the projected return frequency for the 20 and 100-year floods, respectively, as a function of mid-winter temperature regimes. The return frequency for snow dominant basins (depicted with peak flows generally occurring in late spring and early summer) tends to decrease. However, some snowmelt dominant basins are anticipated to undergo an increase in flood risk as a result of saturated soils from more intense spring storms (Salathé 2006) and possible enlargements in contributing basin area as warming increases later in the 21st century (Hamlet et al. 2007).

Basins identified as transient, characterized by a mixed runoff of rain and snow, are projected to be the most sensitive to warming temperatures. These basins are found at higher elevations in coastal mountains (western Cascades, Olympic and Coast Ranges) and at lower elevations in the cooler, continental mountains (Rocky Mountains and eastern Cascades). Transient basins typically have a double-peaked hydrographs (Figure 1, center hydrograph), with one peak greater than the other depending on seasonal inputs to streamflow. Warmer transient basins with peak flows occurring in the winter months are located where precipitation falling as rain seasonally peaks in the winter; whereas cooler, transient basins with a elevated inputs during the spring or early summer have a greater contribution of snowmelt to streamflows. Under a warmer future climate, more winter precipitation falling as rain, rather than snow, will intensify winter flood risk for warmer transient basins. This trend is depicted spatially in the 20 and 100-year flood ratio maps (Figures 3 and 5) showing an overlap in the locations of warmer, transient basins with a progressive increase in flood risk through the 21st century. Likewise, the corresponding scatterplots of projected return frequencies and DJF temperatures (Figures 4 and 6) capture this trend, showing elevated future flood frequencies for basins with winter temperatures fluctuating near freezing and maintaining peak flows in the winter. However, the response of transient basins to warming temperatures is complex, because it is contingent not only on the type and timing of precipitation events, but also on the balance of snow accumulation and change in contributing basin size. If the DJF of the basin is on the cooler spectrum of the winter temperature range, -6 ^{o}C to -3 ^{o}C, then the decline in seasonal snow accumulation tends to lower the flood risk in the spring and early summer (as for snowmelt dominant watersheds). Whereas the flood risk of transient basins characterized by warmer DJFs (> -3 ^{o}C) tends to increase despite losses of antecedent snowpack, primarily because the area of the contributing watershed is enlarged with additional warming due to an elevational shift in the snow line during storms (Hamlet et al. 2007).

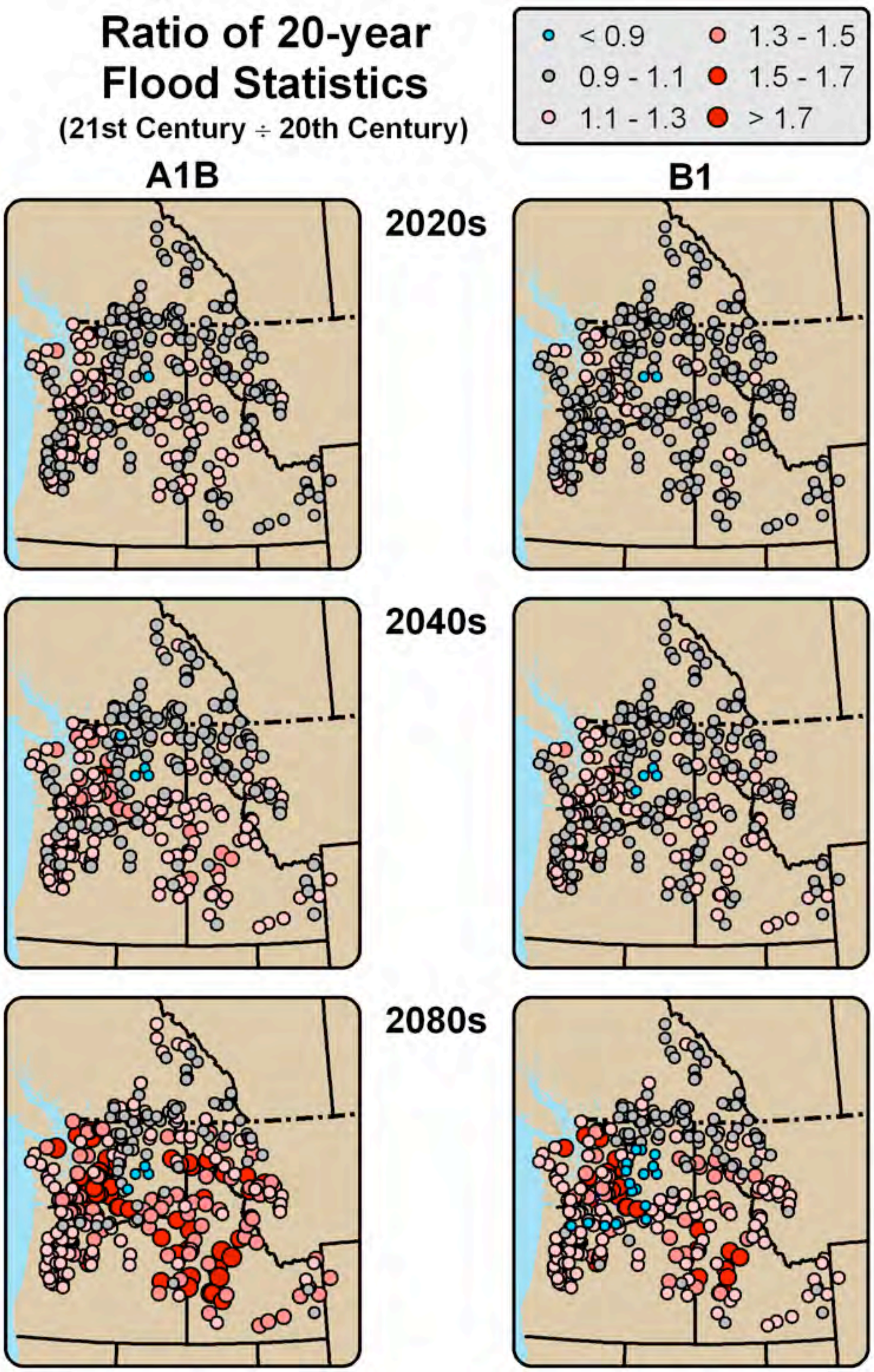

Figure 3: Maps of the ratio of the 20-year flood magnitude (future/ historical) for three future time intervals, under two scenarios. (Higher ratios indicate more intense flooding events projected for the future).

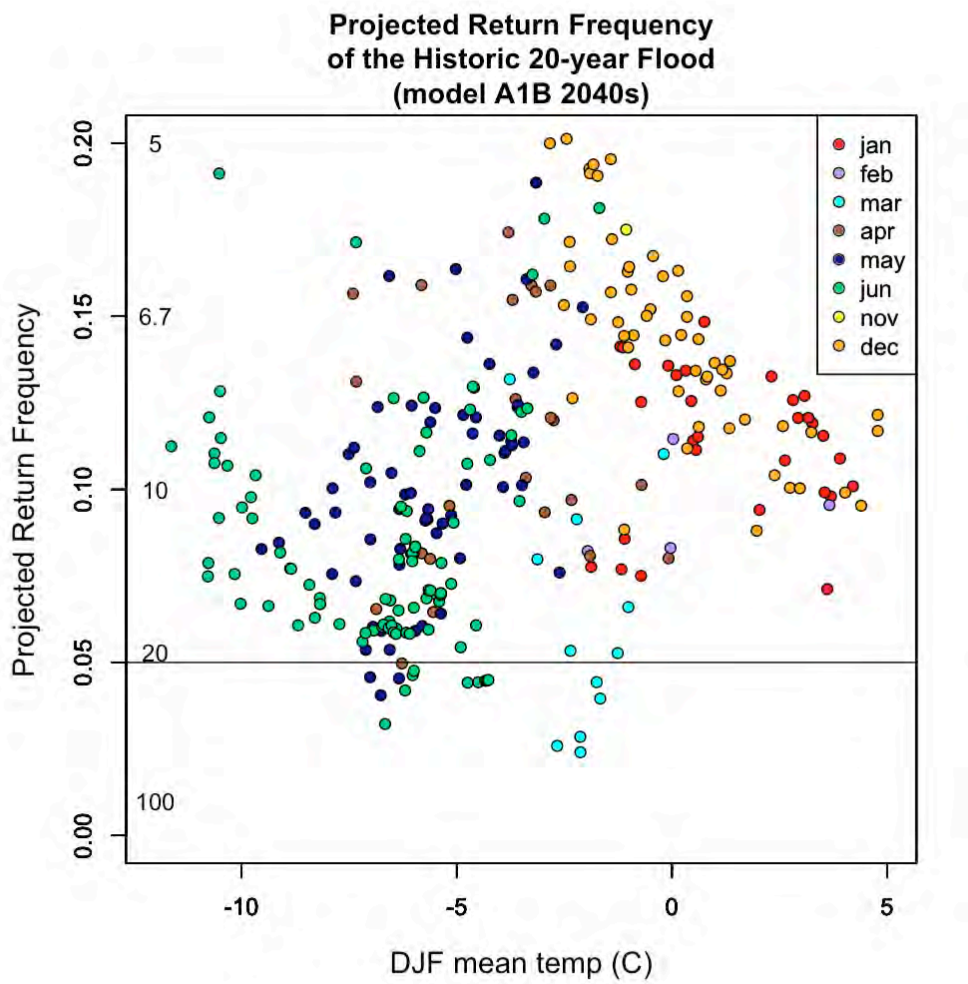

Figure 4: Plots of the mean winter temperature and projected return frequency of the historical 20-year flood for each basin. Colors of dots indicate month of historical flood occurrence.

Projections of flood risk for rain dominant basins do not indicate any significant change under future conditions, although increases in winter precipitation in some scenarios do nominally increase the risk of flooding in winter. Figures 3 and 5 show that the flood risk for rain dominant basins in western Washington and Oregon only slightly increases or does not change with warming temperatures.

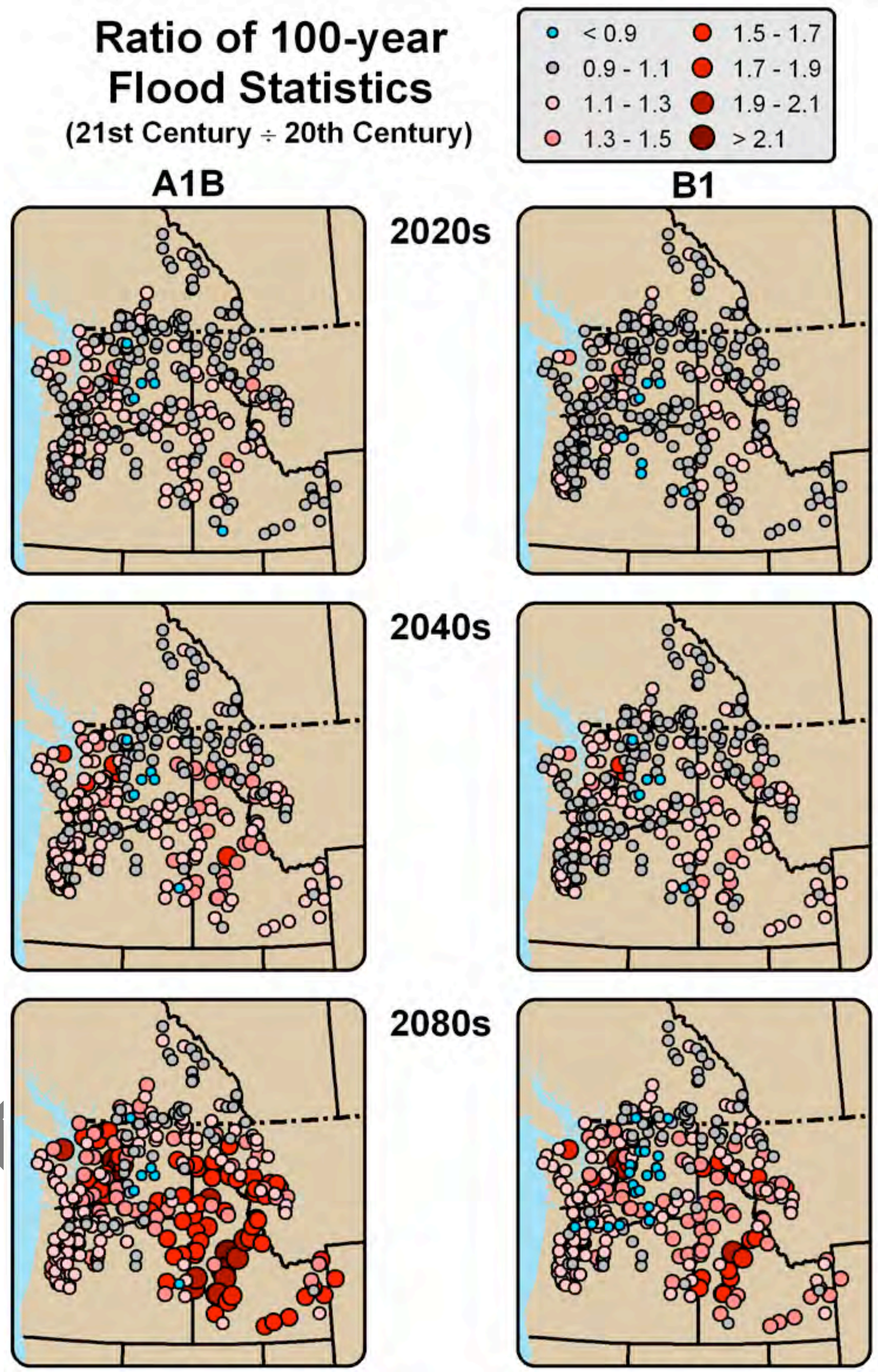

Figure 5: Maps of the ratio of the 100-year flood magnitude (future/ historical) for three future time intervals, under two scenarios. (Higher ratios indicate more intense flooding events projected for the future).

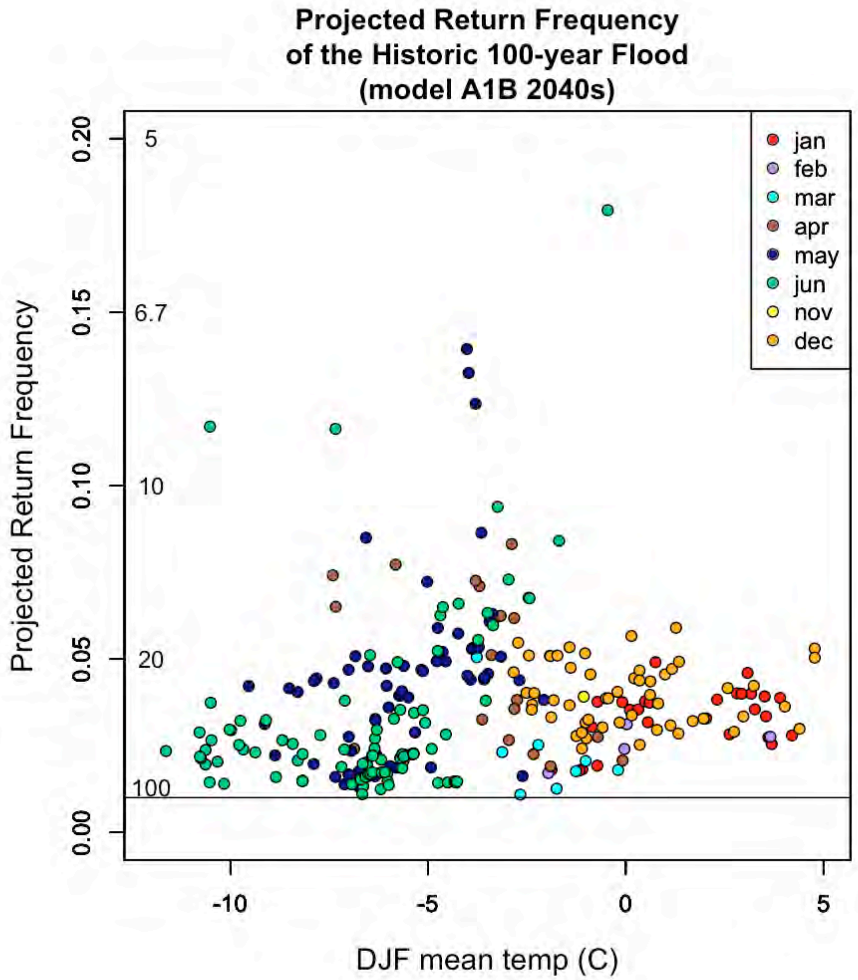

Figure 6: Plots of the mean winter temperature and projected return frequency of the historical 100-year flood for each basin. Colors of dots indicate month of historical flood occurrence.

3.2. Changes in Low flow Risk

Low flow, 7Q10, values are projected to decrease (i.e. increasing low flow risk) most strongly in rain dominant and transient basins (Figure 7). This pattern is particularly prominent in the lower elevation basins of the eastern Cascades and the mid to lower elevation basins in the western Cascades and in the Olympic Peninsula and the lower elevations on the west slopes of the Rockies. These results support the hypothesis that the intensity of the low flows will rise with increasing temperatures and evapotranspiration, which reduces the soil water moisture and late summer baseflows. Unlike transient and rain dominant basins, the changes in low flow regimes projected for snowmelt dominant basins are relatively insensitive to increased temperatures. These basins, which include many tributaries in the Columbia and the Snake basins, demonstrate relatively small decreases in 7Q10. Some of the coldest sites located in the interior of Columbia basin and at the headwaters of both the Columbia and Snake basins demonstrate increases for the in 7Q10 statistics associated with warming (Figure 7). One explanation for the relatively small changes or increases in 7Q10 statistics is that the lowest flows in these coldest basins often occur in the winter when water is trapped as snow. As temperatures warm, shifting these basins to an increasingly transient behavior, and more precipitation falls as rain in the winter months, 7Q10 values may actually rise somewhat for the coldest basins.

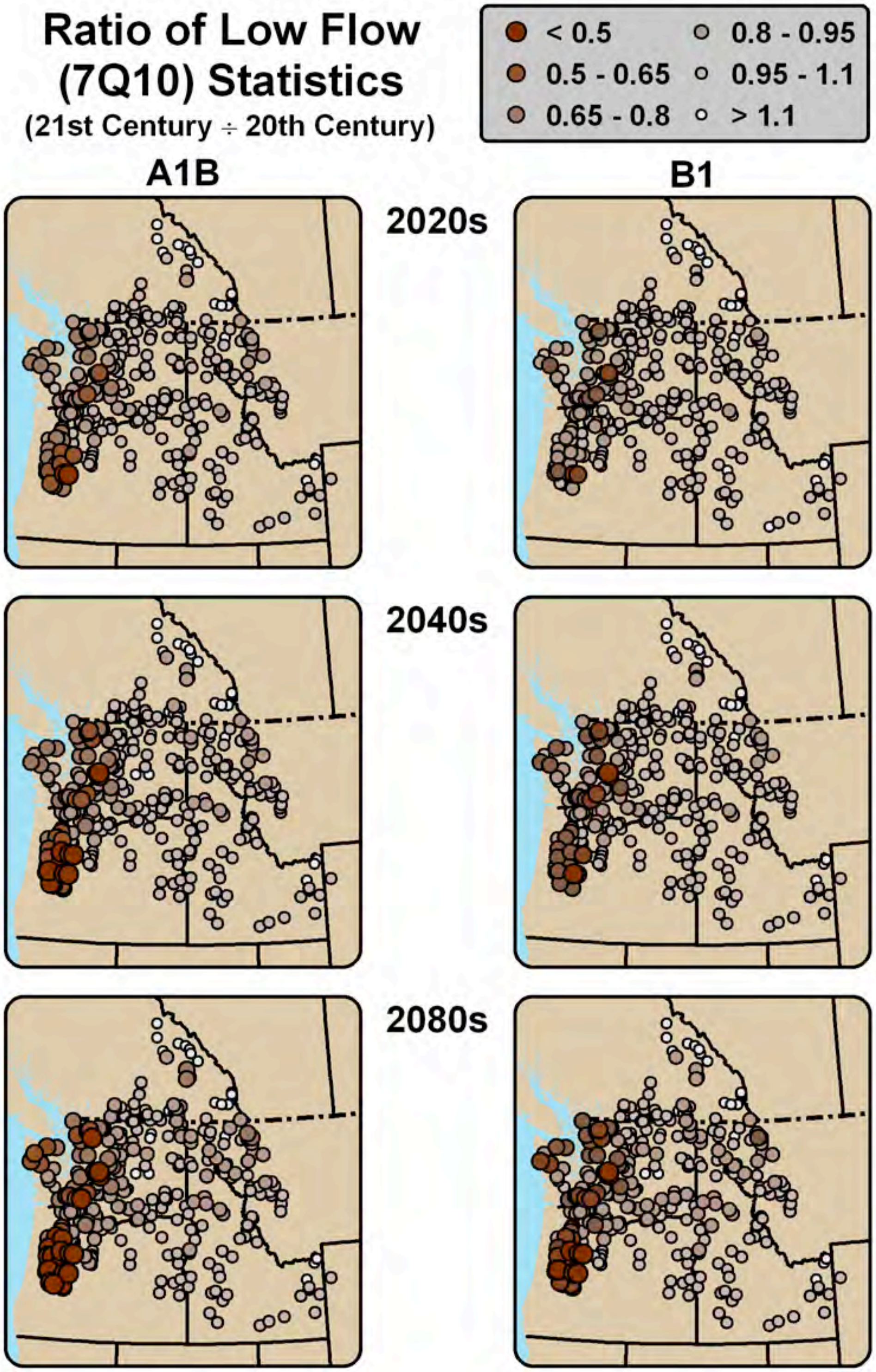

Figure 7: Maps of the ratio of 7Q10 low flow magnitudes (future/historical) for 3 future time intervals, under 2 scenarios. (Lower ratios indicate more intense low flow extremes in the future)

4. Research Gaps

Many of the larger basins contributing to the Columbia River basin are regulated by dam operations and other watershed management practices. Among the limitations of determining extreme flow risks using the methods applied here are the exclusion of management operations. The routed streamflows used to calculate these statistics do not consider managed flows, so this assessment reports only natural flood and low flow risks. Although the simulated streamflows do not represent absolute values of the actual flows in many of these watersheds, it is important to observe the relative streamflows (historical to future). The strength of these analyses lies in what the models indicate is the historical relative to the future simulated streamflows. Another restriction inherent in these models is the lack of incorporation of geomorphological changes in these watersheds.

5. Conclusions

The overall response of the Columbia River basin to warmer temperatures projected in the future to is a general shift in the primary mechanism of streamflow inputs from snowmelt to transient to rainfall dominance. The most sensitive watersheds to this widespread shift in basin type are those found at mid-elevations, where small increases in average winter temperatures can trigger rainfall to predominate as precipitation inputs. The comprehensive conversion in basin type provokes in a shift in the timing of peak flows and base flows. As more precipitation falls in the wintertime as rainfall for transient basins, the winter peak flows are projected to increase and summer flows are projected to decrease as less snowmelt contributes to streamflow.

The projected changes in extreme flow risks are dependent on the responses of basins to the future warming. Flood risk increases for mid-elevation basins with greater rainfall contributions to streamflow. Whereas snow and rainfall dominant basins remain relatively insensitive to greater flood risks with future warming. The low flow risk, likewise, is projected to rise most prominently for the transient basins since the summertime flows will diminish with less snowmelt inputs.

These varied responses of the Columbia River basins have implications for future management operations. The change in timing of flood and low flow risks for sensitive basins needs to be considered for such operations as hydropower generation and maintaining minimum flows for fish passage. Other factors include stream temperatures in the summer in correlation to lower base flows and the impact on fish habitat.

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Streamflow Locations, Sources of Natural Streamflow Data, and Key Hydrologic Products

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1. Introduction

This chapter provides an overview of the streamflow locations supported by the Columbia Basin Climate Change Scenarios Project (CBCCSP), the sources of naturalized streamflow data used for hydrologic model calibration and bias correction, and the key hydrologic products generated by the hydrologic models. These products result from a set of hydrologic model simulations at 1/16th degree resolution implemented over the Columbia River basin (Chapter 5).

A total of 77 hydrologic model simulations are used in the present study. Input data are varied among 10 global climate models (GCMs), 2 emissions scenarios, and 3 downscaling approaches (Chapter 4). Table 1 lists the number of simulations used for each downscaling. In the case of the Hybrid-Delta simulations, a simulation is run for each emissions scenario, future time period, and each of the 10 highest-ranking GCM simulations (Chapter 4). The Delta Method simulations, in contrast, are only run once for each simulation and time period, using a composite of all 10 GCMs to provide inputs for VIC runs. Finally, the Transient runs are performed once for each emissions scenario and each of the 7 highest-ranking GCM simulations.

Note that most of the scenarios are produced using the Hybrid Delta method. The reasons for this choice are discussed in more detail in Chapter 4. To summarize briefly, the choice is based primarily on the fact that the Hybrid Delta method produces the best daily realizations of the three downscaling methods explored, and supports studies at relatively small spatial scales, both of which are key needs in the current study (Chapters 1 & 2).

Table 1 – Matrix of climate change scenarios included in the study. Numbers in the table show the number of GCM scenarios used for each downscaling approach and/or time period. Note that data for the B1 emissions scenario was not available from one of the 10 GCMs used in the Hybrid Delta simulations.

Downscaling Approach		A1B Emissions Scenario	B1 Emissions Scenario
Hybrid Delta	2020s	10	9
	2040s	10	9
	2080s	10	9
Transient BCSD*	--	7	7
Delta Method	2020s	1	1
	2040s	1	1
	2080s	1	1

*Bias-Corrected Statistical Downscaling

The products described below are all archived and available on the project website (Chapter 9, http://www.hydro.uw.edu/2860/), and are either displayed on the site itself or linked via ftp.

2. Primary Macro-Scale Hydrologic Products

The Variable Infiltration Capacity (VIC) macro-scale hydrologic model can be configured to archive a number of hydrologic variables that are produced at daily time step during the simulations. In the present study, specific output variables are selected based on the survey of potential users (Chapter 2) and the usefulness of these hydrologic variables in past water planning case studies incorporating climate change. Table 2 lists the variables that are archived in the present study, as well as notes regarding the definition of each variable, its units, and the method used for computing the monthly summary of each.

Results are archived for the historical as well as each of the 77 VIC runs described above (see Table 1). The raw VIC output is stored in a separate file for each grid cell. These raw output files are referred to as “flux” files and are zipped into a single file and available for download on the ftp site. The meteorological input data for each simulation are also made available for download. Each flux file contains one row for each day of the 92-year simulations (a total of 33,603 rows). The first 3 columns in each row record the date (year month day), while the following 21 columns record the value of each variable for that day, following the order provided in Table 2. This raw output from VIC forms the basis for all of the products described below.

Table 2 – VIC hydrologic model output variables. The variables are displayed in the order that they are archived in the raw VIC output files. Monthly summaries are archived for each of these variables, both in time series and gridded formats. The right-hand column shows the method used to aggregate monthly output for each variable.

ID	Abbrev.	Output Variable	Notes	Units	Summary Type
1	precip	Daily total precipitation		mm	Monthly total
2	tavg	Daily average temperature		˚C	Monthly average
3	tmax	Daily maximum temperature		˚C	Monthly average
4	tmin	Daily minimum temperature		˚C	Monthly average
5	olr	Outgoing longwave radiation		W/m^2	Monthly average
6	isr	Incoming shortwave radiation	solar radiation	W/m^2	Monthly average
7	rh	Relative humidity		%	Monthly average
8	vpd	Vapor pressure deficit		Pa	Monthly average
9	et	Daily evapotranspiration		mm	Monthly total
10	runoff	Daily Runoff		mm	Monthly total
11	baseflow	Daily Baseflow		mm	Monthly total
12	soilm1	Soil Moisture, Layer 1		mm	1st of month
13	soilm2	Soil Moisture, Layer 2		mm	1st of month
14	soilm3	Soil Moisture, Layer 3		mm	1st of month
15	swe	Snow water equivalent	total water content of the snowpack	mm	1st of month
16	snodep	Snow depth		cm	1st of month
17	pet1	Potential Evapotranspiration 1	natural vegetation, no water limit	mm	Monthly total
18	pet2	Potential Evapotranspiration 2	open water surface (fixed albedo)	mm	Monthly total
19	pet3	Potential Evapotranspiration 3	natural vegetation, no water limit, no vegetation resistance	mm	Monthly total
20	pet4	Potential Evapotranspiration 4	Tall reference crop (alfalfa)	mm	Monthly total
21	pet5	Potential Evapotranspiration 5	Short reference crop (short grass)	mm	Monthly total

Four general categories of hydrologic products are available from this study:

1. Streamflow simulations at the sites selected for this study
2. Bias-corrected inflows to support specific reservoir simulation models
3. Gridded datasets of the key hydrologic variables listed in Table 2
4. Site specific data and summary products for each streamflow location

The post-processing steps used to produce these products are illustrated in the flow chart shown in Figure 1. The sections below provide additional details on each of the products.

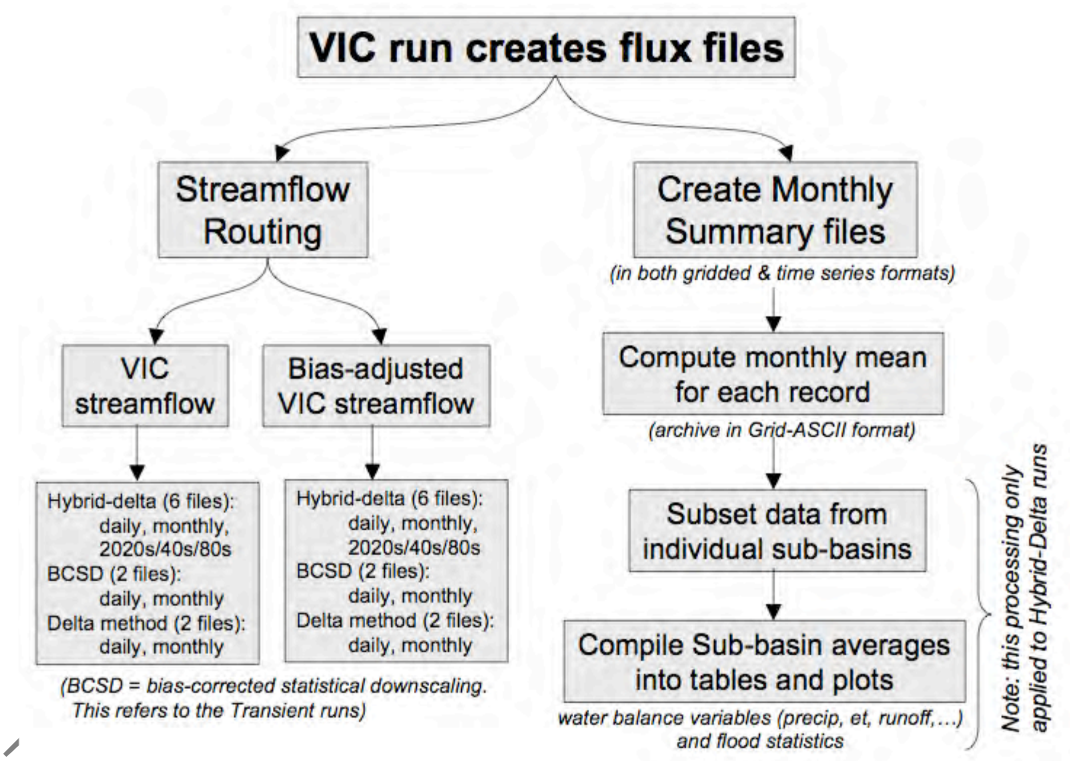

Figure 1 – Flow chart illustrating the post-processing steps used to produce the hydrologic products made available from the present study.

3. Streamflow Simulations and Sites Selected for Routing

A post-processing step routes the runoff and baseflow from each grid cell in the model to estimate daily streamflow at the streamflow sites chosen for the study (Figure 2). The 297 streamflow sites were selected based on two criteria: a) usefulness of the site for planning, and b) contributing upstream basin area larger than 500 km^2 (approximately 200 sq mi). These sites were chosen in close consultation with the study partners (see Chapter 1). A database offering more detailed information about each of the selected sites is provided on the study website (Chapter 9, http://www.hydro.uw.edu/2860/).

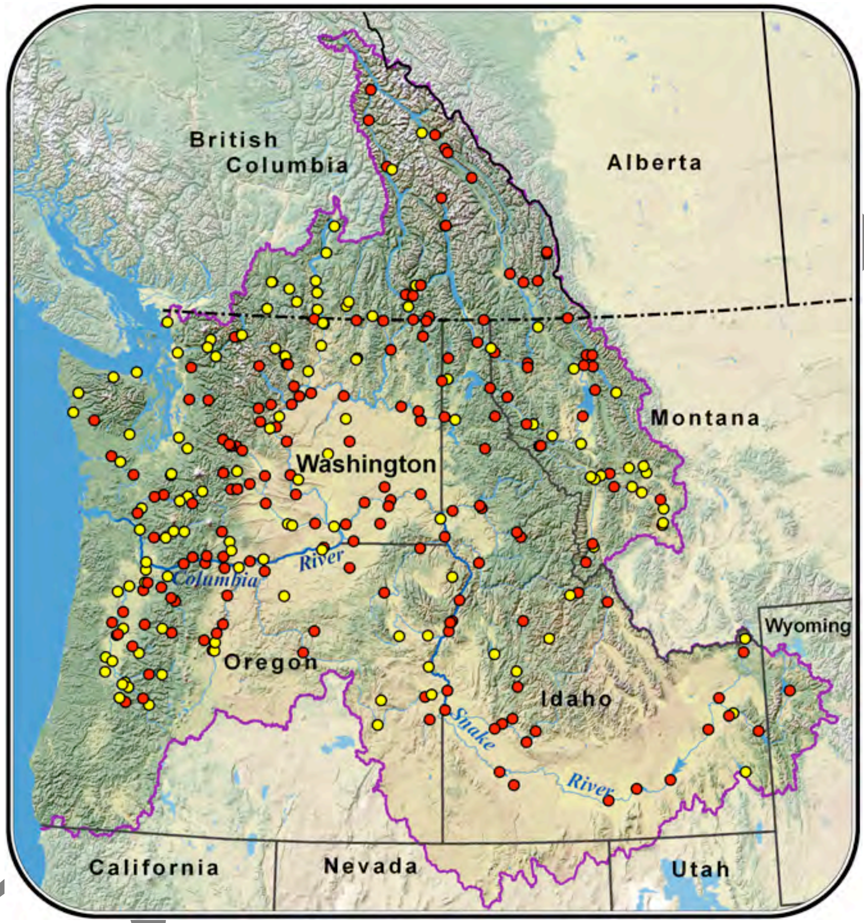

Figure 2 Map of the selected streamflow locations supported by the study. Red dots indicate sites that are essentially unimpaired by human use or for which there is estimated modified or naturalized flow. Sites without natural flow estimates are shown in yellow.

3.1 Sources of Naturalized Streamflow Data

Naturalized or modified flow is available at a number of locations in the Columbia basin (Figure 2). These data are estimated by naturalization studies prepared for the Bonneville Power Administration (BPA; A.G. Crook, 1993), the Washington State Dept. of Ecology (WDOE; Flightner, 2008), the Oregon Department of Water

Resources (ODWR; Cooper, 2002), the Idaho Department of Water Resources (IDWR; personal communication), and the U.S. Bureau of Reclamation (USBR; personal communication). In addition, some observed streamflow data is suitable for use as natural data if the effects of storage and diversions is relatively small (*e.g.*, for the USGS Hydro-Climatic Data Network sites).

Naturalized streamflow data are used both to calibrate the hydrologic model (Chapter 5) and to produce bias-corrected streamflow realizations using quantile mapping techniques described by Snover et al. (2003), Elsner et al. (2009), and Vano et al. (2009). These techniques remove systematic biases in the simulations of routed streamflow to produce products that very closely match the long-term statistics and time series behavior of a natural or modified flow dataset for a particular site. These data are often very useful in water planning studies, especially for the purpose of providing inputs to reservoir operations models that are calibrated on a particular naturalized flow dataset (*e.g.*, NWPCC 2005, Hamlet et al. 2009, Vano et al. 2009). These approaches are also very useful for avoiding biases in the streamflow simulations that result from systematic errors in gridded precipitation or temperature data (the key inputs to the hydrologic models). Such errors are commonly encountered at relatively small spatial scales, particularly when meteorological stations are sparse, and often cannot be resolved using conventional hydrologic model calibration strategies (see Chapter 4 for further discussion). Bias correction procedures provide an alternate statistical approach that effectively avoids these difficulties (Shi et al. 2008). All streamflow data for each sub-basin are made available for download on the ftp site, following the file naming conventions described in Table 5.

3.2 Reservoir Model Inputs

Bias corrected inflows to support three existing reservoir simulation models are supported in the scope of work for the current study. These models are the basin-wide GENESYS and HYDSIM models, which are used by the BPA and Northwest Power and Conservation Council (NWPCC 2005) respectively for mainstem studies in the Columbia basin. A third product provides naturalized inflows at model nodes needed to run the USBR MODSIM reservoir model for the Snake River basin (Labadie, 2007). These data are provided, in an agreed upon format, via an ftp site linked to the study web site (Chapter 9). Data for each model and scenario are stored in a unique directory on the ftp site in ascii format.

4. Description of Summary Hydrologic Products

This section describes the summary hydrologic products generated as part of the post-processing (shown on the right-hand side of Figure 1).

4.1 Gridded Datasets

Gridded datasets provide full spatial coverage (i.e., all grid cells in the model domain), at monthly time scale, of the key hydrologic variables using the monthly aggregation scheme listed in Table 2. Each product is provided as a gridded file (one file for each variable and calendar month) in ASCII format.   The rows of these files are water years (e.g., WY 1916-2006 for the Hybrid Delta products), and the 24,108 columns contain the unique values for each grid cell in the model (i.e. a latitude/longitude position for each grid cell in the domain). The first two rows of the files give the latitude and longitude, respectively, of each grid cell location and the rows below are populated with the monthly data for each year from 1916 to 2006. By way of an example, gridded snow water equivalent (SWE) is summarized by taking data from the first day of each month (Table 2, example file name: “swe_monthly_day1_apr”). As a consequence, the April 1 summary file for SWE will have 93 rows (one each for latitude and longitude followed by one for each water year) and 24,108 columns (one for each grid cell). There will be a total of 12 such files that provide the summary for SWE for each of the simulations listed in Table 1.

For convenience, the monthly summaries are also organized into separate time series files for each grid cell in the model domain. Each time series file contains one row for each month and year in the simulations. Columns denote the year and month, followed by the monthly summaries for the 21 variables listed in Table 2. As above, the monthly aggregation for each variable follows that listed in Table 2. The data included in the time series files is exactly the same as that included in the monthly summaries described above, but is separated by grid cell rather than by variable and month. These additional files are included for convenience, since some users may find the latter format most suitable to their needs.

Table 3 – Description of GridASCII file format.

Row number	*Contents in file*	*Description*
row 1:	ncols xxx	integer number of columns
row 2:	nrows xxx	integer number of rows
row 3:	xllcorner xxx	longitude of the lower-left corner (lower-left corner of grid cell)
row 4:	yllcorner xxx	latitude of the lower-left corner (lower-left corner of grid cell)
row 5:	cellsize xxx	cell spacing
row 6:	NODATA_value xxx	default is -9999
row 7-end:	regularly gridded data	space-delimited, floating point.

In addition to the time series data, the long-term monthly mean data of each hydrologic variable is provided in GridASCII format, compatible with ArcGIS. Although GridASCII format is a standard developed for use with ArcInfo, the format is quite simple and other data processing software can easily be adapted to read in this file format. GridASCII files store regularly gridded latitude/longitude data based on the descriptors defined in the header for each file. The data are gridded so that the top row corresponds to the northernmost latitude, decreasing to the southernmost latitude in the final row. Columns thus correspond to variations in longitude, where the leftmost column corresponds to the western extent, and the rightmost column the eastern extent of the domain. The header in each GridASCII file describes the position and spacing of the grid as well as the format of the data. A description of the GridASCII header is given in Table 3, and further information can be obtained from the ESRI help website (http://webhelp.esri.com, search for: “ESRI ASCII Raster format”). Figure 3 shows a set of example maps generated using ArcGIS. Results for April 1 SWE are plotted over the entire study domain, including the historical as well as the six composite Delta Method scenarios that correspond to the two climate scenarios (A1B and B1) and three future time periods (2020s, 2040s, and 2080s).

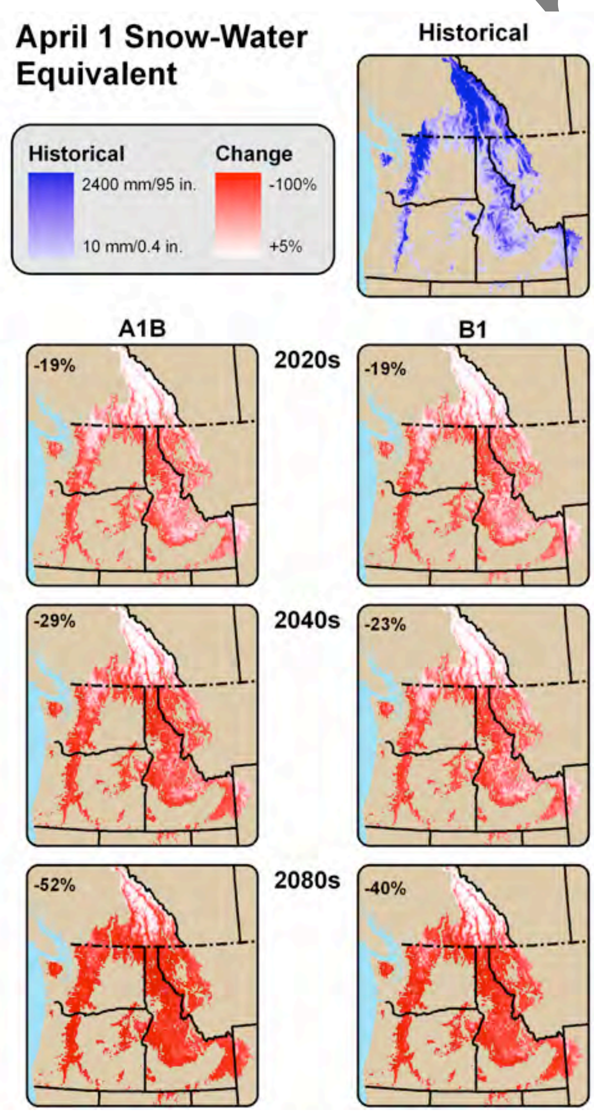

Figure 3 – Long-term mean of April 1 SWE for historic and six composite delta scenarios.

The above products (summary files and GridASCII files) are available for all 77 climate scenarios listed in Table 1, as well as for the historical record. Additional products are provided only for the Hybrid-Delta scenarios. These are the water balance (described below) and extreme event (Chapter 7) summaries for each specific streamflow site.

4.2 Site-Specific Products

For each streamflow location (and its associated contributing basin area), a set of identical products are available on the study web site (Chapter 9, this report). These products are all listed in Table 4 and described in this section.

Table 4 - List of site-specific products provided for each streamflow location. The 2 right-hand columns give the number of files archived in each category (blank cells imply that no such files are created).

Product		**File Naming Convention** *(file name for A1B 2020s is used as an example)*	**Image**	**Table**
Location description			**1**	**1**
Water Balance Summary ***(Hybrid-Delta runs only)***	Precipitation	precip_monthly_tot_hd_A1B_2010-2039.dat	**1**	**6**
	Temperature (daily average)	tavg_monthly_avg_hd_A1B_2010-2039.dat	**1**	**6**
	Evapotranspiration	et_monthly_tot_hd_A1B_2010-2039.dat	**1**	**6**
	Potential Evapotranspiration 4	pet4_monthly_tot_hd_A1B_2010-2039.dat	**1**	**6**
	Potential Evapotranspiration 5	pet5_monthly_tot_hd_A1B_2010-2039.dat	**1**	**6**
	Soil Moisture (3 layer total)	soilmoist_monthly_day1_hd_A1B_2010-2039.dat	**1**	**6**
	Snow Water Equivalent	swe_monthly_day1_hd_A1B_2010_2039.dat	**1**	**6**
	Combined flow (runoff+baseflow)	combinedflow_monthly_tot_hd_A1B_2010-2039.dat	**1**	**6**
	Flood Statistics	floodstats_daily_hd_A1B_2010-2039.dat	**1**	**6**
	Low Flow Statistics	lowflow_stats_7q10_hd_A1B_2010-2039.dat	**1**	**6**
VIC Daily Streamflow	Historical	VIC_streamflow_daily_historical.dat		**1**
	Hybrid Delta (60 scenarios)	VIC_streamflow_daily_hd_2020.dat		**3**
	Transient BCSD (10 scenarios)	VIC_streamflow_daily_tr.dat		**1**
	Composite Delta (6 scenarios)	VIC_streamflow_daily_dt_2020.dat		**3**

VIC Monthly Streamflow	Historical	VIC_streamflow_monthly_historical.dat		**1**
	Hybrid Delta (60 scenarios)	VIC_streamflow_monthly_hd_2020.dat		**3**
	Transient BCSD (10 scenarios)	VIC_streamflow_monthly_tr.dat		**1**
	Composite Delta (6 scenarios)	VIC_streamflow_monthly_dt_2020.dat		**3**
Bias Corrected Daily Streamflow Data*	Historical	Nat_bias_adjusted_vic_daily_hd_historical.dat or Mod_bias_adjusted_vic_daily_hd_historical.dat		**1**
	Hybrid Delta (60 scenarios)	Nat_bias_adjusted_vic_daily_hd_2020.dat or Mod_bias_adjusted_vic_daily_hd_2020.dat		**3**
	Transient BCSD (10 scenarios)	Nat_bias_adjusted_vic_daily_tr.dat or Mod_bias_adjusted_vic_daily_tr.dat		**1**
	Composite Delta (6 scenarios)	Nat_bias_adjusted_vic_daily_dt_2020.dat or Mod_bias_adjusted_vic_daily_dt_2020.dat		**3**
Bias Corrected Monthly Streamflow Data*	Historical	Nat_bias_adjusted_vic_monthly_hd_historical.dat or Mod_bias_adjusted_vic_monthly_hd_historical.da		**1**
	Hybrid Delta (60 scenarios)	Nat_bias_adjusted_vic_monthly_hd_2020.dat or Mod_bias_adjusted_vic_monthly_hd_2020.dat		**3**
	Transient BCSD (10 scenarios)	Nat_bias_adjusted_vic_monthly_tr.dat or Mod_bias_adjusted_vic_monthly_tr.dat		**1**
	Composite Delta (6 scenarios)	Nat_bias_adjusted_vic_monthly_dt_2020.dat or Mod_bias_adjusted_vic_monthly_ dt_2020.dat		**3**

**subject to availability of naturalized or modified flow data*

The site location is identified via a map of the basin and a brief table of geographic information (such as the site name, latitude, longitude, basin area, USGS number, etc.). Following these are a series of eight figures and associated data files summarizing the key water balance variables and the statistics of extreme events for the hybrid delta scenarios. These figures all have the same format, an example of which is shown in Figure 4. Each of the six panels in the figure shows the monthly mean for the 10 hybrid-delta GCM scenarios (red) as well as the historical average (blue). For the future scenarios, both the ensemble mean (solid line) and the range of values (shading) are plotted. The six panel display results for each future time period (rows) and emissions scenario (columns). Data files (six per figure) providing all the ensemble members used to construct each panel in the figure are also provided (example shown in Table 5).

Table 5 – Format of data table associated with each panel shown in Figure 4. As in Figure 4, example results are shown for the basin that drains into the Columbia River at the Dalles river site (#4030). The table shows the basin summary for the 2040s and the A1B scenario. The first three columns give the month and the historical means, while each subsequent column includes the results for each of the 10 global models discussed in Chapter 4. For clarity, only the first 6 columns are displayed.

mnum	mnth	hist	ccsm3	cgcm3.1_t47	cnrm_cm3	…
01	oct	0.40	0.08	0.12	0.06	…
02	nov	6.39	4.21	6.44	5.28	…
03	dec	34.91	32.29	32.28	35.74	…
04	jan	82.42	77.34	76.42	76.98	…
05	feb	133.70	114.42	121.78	122.57	…
06	mar	157.20	120.14	136.94	147.45	…
07	apr	152.59	115.72	129.17	145.58	…
08	may	112.21	84.62	97.45	106.71	…
09	jun	49.99	28.52	40.56	41.68	…
10	jul	11.07	3.55	7.85	5.46	…
11	aug	0.82	0.06	0.28	0.12	…
12	sep	0.17	0.00	0.02	0.00	…

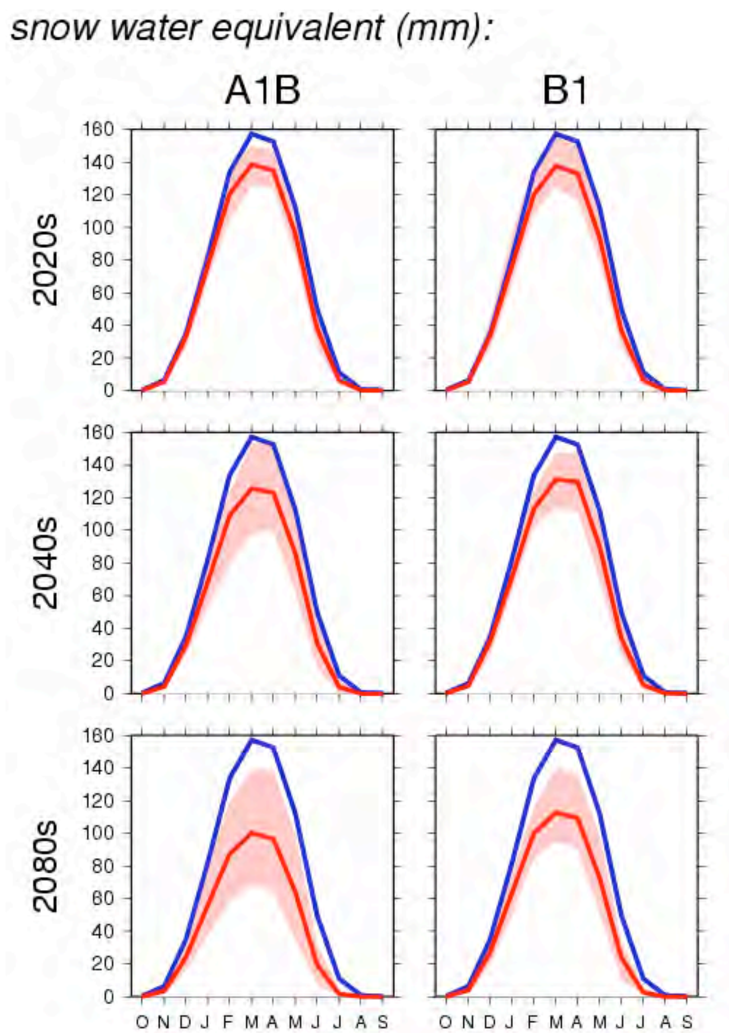

Figure 4 – Example of summary plot for SWE for the basin that drains into the Columbia River at The Dalles, OR (#4030). (Note figure will be updated as runs are completed)

Daily and monthly streamflow products are also provided for each downscaling method. Results from all of the ensemble members are provided in each case. The data are organized in tables: For the Hybrid Delta downscaling method (Chapter 4), water balance variables are summarized for each month and for each GCM. One such table is provided for each time period (2020s, 2040s, 2080s) and each emissions scenario (A1B, B1). Streamflow data are also summarized in this format, with additional tables included for the Transient (14 columns: one per global model, one file per time period) and Composite Delta (2 columns: one for each scenario, one file per time period) simulations. If naturalized streamflow data (or unimpaired observed data) exist for the site, then a set of bias corrected streamflow files is also provided in the same format as the raw simulations.

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Overview of Website Design and Implementation

(Website development is in progress and the documentation describing these study products will follow the completion of the site in December, 2009.)

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