

# **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 study that are provided on the study website (<http://www.hydro.washington.edu/2860/>). These products result primarily from a set of hydrologic model simulations at 1/16<sup>th</sup> degree resolution implemented over the Columbia River basin (Chapter 5, this report).

One historical run, and a total of 77 hydrologic model scenarios are used in the present study, based on data from 10 global climate models (GCMs), 2 emissions scenarios, and 3 downscaling approaches (Chapter 4, this report). 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 emissions scenario and time period, using a composite of temperature and precipitation changes from 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).

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.

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.

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

\*Bias-Corrected Statistical Downscaling

## 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 were 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 summaries of each.

Results are archived for a single historical run as well as each of the 77 future 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.

<b>ID</b>	<b>Abbrev.</b>	<b>Output Variable</b>	<b>Notes</b>	<b>Units</b>	<b>Summary Type</b>
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 <sup>2</sup>	Monthly average
6	isr	Incoming shortwave radiation	solar radiation	W/m <sup>2</sup>	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	1 <sup>st</sup> of month
13	soilm2	Soil Moisture, Layer 2		mm	1 <sup>st</sup> of month
14	soilm3	Soil Moisture, Layer 3		mm	1 <sup>st</sup> of month
15	swe	Snow water equivalent	total water content of the snowpack	mm	1 <sup>st</sup> of month
16	snodep	Snow depth		cm	1 <sup>st</sup> 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	Tall reference crop	mm	Monthly total

		Evapotranspiration 4	(alfalfa)		
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 specific sites selected for this study (currently 297 sites)
2. Summary figures and data for each streamflow location
3. Gridded datasets of the key hydrologic variables listed in Table 2
4. Bias-corrected inflows to support specific reservoir simulation models

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.

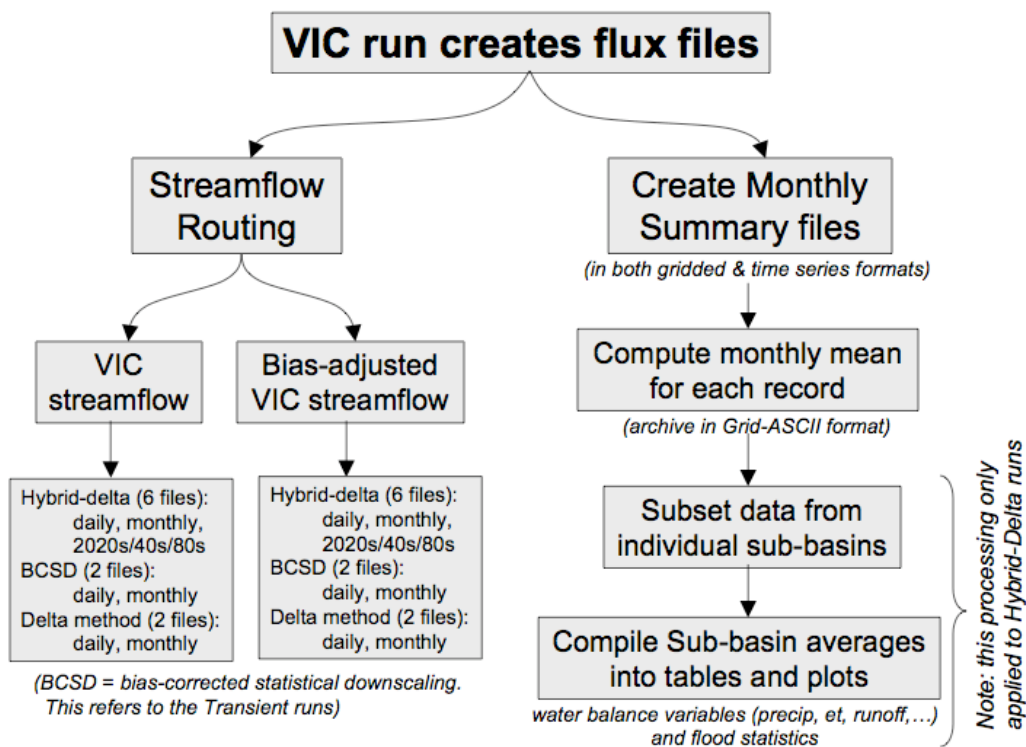


Figure 1 – Flow chart illustrating the post-processing steps used to produce the hydrologic products made available from the present study.

### 3. Meteorological Data for Urban Centers to Support Power Demand Modeling

Meteorological data such as daily minimum and maximum temperatures are required to estimate power generation by uses such as the Northwest Power and Conservation Council (NPCC). To support these kinds of studies flux files for major urban centers in the PNW (listed in Table 3) are stored at a single ftp site which is linked with the study website ([http://www.hydro.washington.edu/2860/products/primary\\_data/](http://www.hydro.washington.edu/2860/products/primary_data/)). The hierarchy of the directory structure for the ftp site in the web page is shown in Figure 2.

Table 3- Latitude and longitude for urban centers for power estimation by Northwest Power and Conservation Council (NPCC).

Urban Centers	Latitude	Longitude
Portland PDX	45.5896	-122.5921
SeaTac	47.6062	-122.3321
Boise Airport	43.5704	-116.2216
Spokane Airport	47.6250	-117.5375

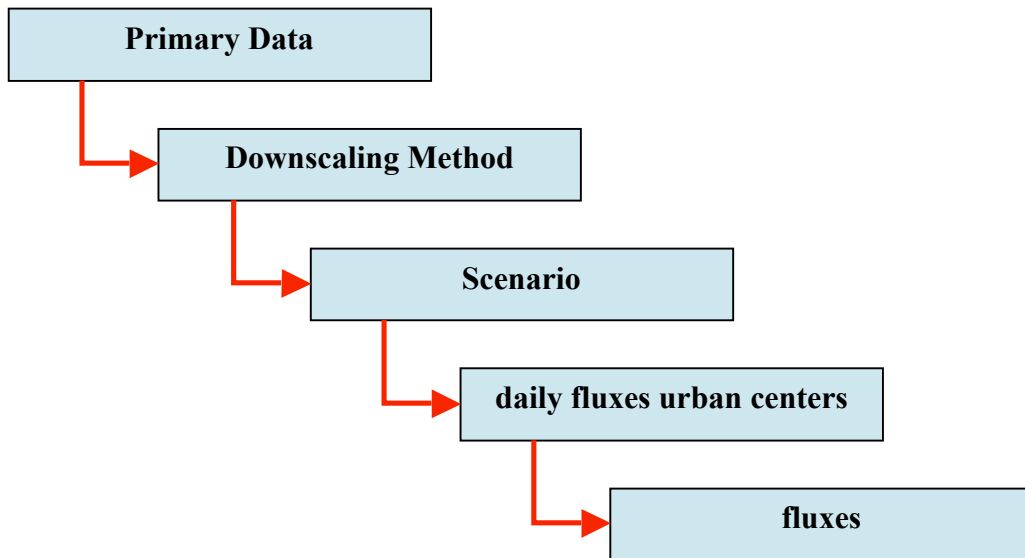


Figure 2 – Flow chart illustrating the hierarchy of the directory structure for the ftp site of the flux files for urban centers requested by Northwest Power and Conservation Council (NPCC).

#### 4. 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 3). 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 approximately 200 sq mi (500 km<sup>2</sup>). 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 stored in a spreadsheet which is linked to study website (<http://www.hydro.washington.edu/2860/products/sites/>).

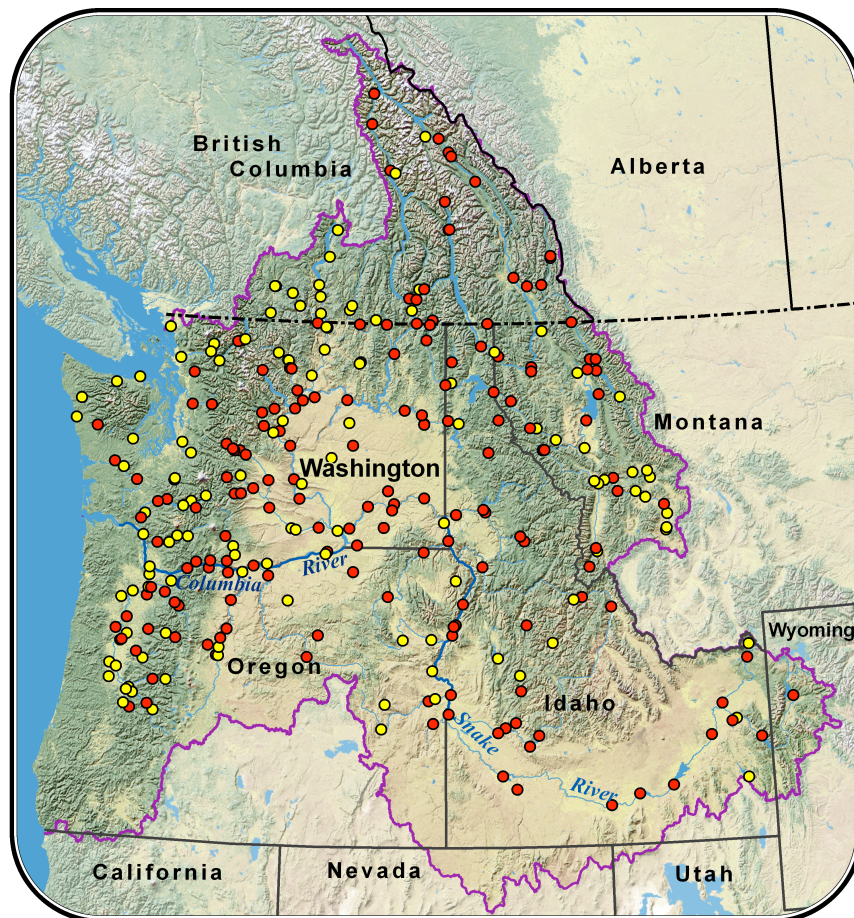


Figure 3 - Map of the selected streamflow locations supported by the study. Red dots indicate sites that are essentially unimpaired by human use or for which there is estimated modified or naturalized flow. Sites without natural flow estimates are shown in yellow.

#### **4.1 Sources of Naturalized Streamflow and Depletion Data**

Naturalized or modified flow is available at a number of locations in the Columbia basin (Figure 3). These data are estimated by naturalization studies prepared for the Bonneville Power Administration (BPA; 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 are relatively small (*e.g.*, for the USGS Hydro-Climatic Data Network sites). Naturalized or modified streamflow data are used both to calibrate the hydrologic model (Chapter 5) and to produce bias-corrected streamflow realizations as described in following section. Source of naturalized and/or modified flow data for each site are recorded in the spreadsheet (<http://www.hydro.washington.edu/2860/products/sites/>).

2006 level of development total depletions such as irrigation and municipal and industrial depletions are estimated by the Washington State Dept. of Ecology (WDOE; Flightner 2008). These data are used to compute bias corrected monthly streamflow with depletions (see below).

#### **4.2 Bias Correction Procedures**

A bias correction procedure using quantile mapping techniques are applied to produce the monthly time step streamflow simulation for the site which has Naturalized or modified flow as described in Snover *et al.* (2003), Elsner *et al.* (2010), and Vano *et al.* (2010). 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. The bias-corrected monthly values are then used to rescale the simulated daily flow sequences produced by the hydrologic model to produce bias corrected daily streamflows. This technique introduces sometimes an undesirable discontinuity in the bias corrected daily values from the end of the month to the beginning of the next month. To minimize this

artifact between months, boundaries between months are smoothed while keeping sum of daily streamflow equal to monthly value. Although the time series behavior of these simulated daily flows are not always identical to the observed naturalized or modified data, the daily flow duration curves are faithfully reproduced overall for each month.

These bias corrected values 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.* 2010, Vano *et al.* 2010). 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).

Either naturalized or modified flows are used for bias correction of data provided in the site-specific products. If the site has sufficient naturalized and modified streamflow data, the site is biascorrected using naturalized flow. If sufficient naturalized flow is not available, the streamflow data for a particular site is bias corrected using modified streamflow if sufficient modified flow data is available. Thus each site is bias corrected using either naturalized or modified flow, but not both. If neither naturalized nor modified flow is available, no bias adjusted data appears on the site. (Note, however, that reservoir model inflow products may use modified flows for bias correction, even if naturalized flows exist for the site, depending on what inputs are required by the model.)

As noted above, in some cases detailed depletions data is available for specific sites and an alternate modified flow product is produced by bias correcting naturalized flows, and then subtracting the estimated net depletions. The bias corrected values with depletion are archived in spreadsheets in the site specific data products.

(<http://www.hydro.washington.edu/2860/sites/>). For example, the spreadsheet named

“nat\_bias\_adjusted\_w\_dep\_vic\_streamflow\_monthly\_his\_dt.xls” shows bias corrected values with depletion for historical and delta method runs. These files only appear for sites that have the necessary depletions data available (see below).

## 5. 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).

### 5.1 Site-Specific Products

For each streamflow location (and its associated contributing basin area), a set of identical products is available on the study web site (Chapter 9, this report). These products are all listed in Table 5 and described in this section. Note that unlike the raw VIC flux files discussed above, English units are used for these products (cfs, inches, degrees F). (This choice was made since these products and data are most likely to be accessed by the general public, who, in the U.S., may not be adequately familiar with metric units.)

Table 5 - 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 <i>(file name for A1B 2020s is used as an example)</i>	Image	Table
Location description			1	1
Water Balance Summary <i>(Hybrid-Delta runs only)</i>	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_streamflow_daily_historical.dat or mod_bias_adjusted_vic_streamflow_daily_historical.dat		1
	Hybrid Delta (60 scenarios)	nat_bias_adjusted_vic_streamflow_daily_hd_2020.dat or mod_bias_adjusted_vic_streamflow_daily_hd_2020.dat		3
	Transient BCSD (10 scenarios)	nat_bias_adjusted_vic_streamflow_daily_tr.dat or mod_bias_adjusted_vic_streamflow_daily_tr.dat		1
	Composite Delta (6 scenarios)	nat_bias_adjusted_vic_streamflow_daily_dt_2020.dat or mod_bias_adjusted_vic_streamflow_daily_dt_2020.dat		3
Bias Corrected Monthly Streamflow Data*	Historical	nat_bias_adjusted_vic_streamflow_monthly_historical.dat or nat_bias_adjusted_w_dep_vic_streamflow_monthly_his_dt.xls or mod_bias_adjusted_vic_streamflow_monthly_historical.dat		1
	Hybrid Delta (57 scenarios)	nat_bias_adjusted_vic_streamflow_monthly_hd_2020.dat or nat_bias_adjusted_w_dep_vic_streamflow_monthly_hd.xls or mod_bias_adjusted_vic_streamflow_monthly_hd_2020.dat		3
	Transient BCSD (14 scenarios)	nat_bias_adjusted_vic_streamflow_monthly_tr.dat or nat_bias_adjusted_w_dep_vic_streamflow_monthly_tr.xls or mod_bias_adjusted_vic_streamflow_monthly_tr.dat		1
	Composite Delta (6 scenarios)	nat_bias_adjusted_vic_streamflow_monthly_dt_2020.dat or nat_bias_adjusted_w_dep_vic_streamflow_monthly_his_dt.xls or mod_bias_adjusted_vic_streamflow_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 streamflow tables for raw and/or bias-adjusted data, 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. Daily and monthly streamflow tables are provided for each downscaling method as well as for historical run. Streamflow data are summarized for each month (or for each day), for each GCM, and for each emissions scenario (A1B, B1). For the Composite Delta and the Hybrid Delta, one table is provided for each time period (2020s, 2040s, 2080s). If naturalized streamflow data (or unimpaired observed data) or modified streamflow data exist for the site, then a set of bias corrected streamflow files is also provided in the same format as the raw simulations. For the site which has 2006 level of development total depletion, the depletion is added up to bias corrected streamflow files to compute the bias corrected streamflow with depletion based on the assumption that 2006 level of development depletion can be applied for climate change run as well as for historical run. The bias corrected streamflows with depletion are summarized in excel files which are archived in the site-specific pages.

## **5.2 Summary Figures and Data**

The figures all have the same format, an example of which is shown in Figure 5. 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 6).

Table 6 – Format of data table associated with each panel shown in Figure 5. As in Figure 5, 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	.....
1	oct	0.01574	0.00314	0.00472	0.00236	.....
2	nov	0.25157	0.16574	0.25354	0.20787	.....
3	dec	1.37440	1.27125	1.27086	1.40708	.....
4	jan	3.24487	3.04487	3.00865	3.03070	.....
5	feb	5.26376	4.50471	4.79447	4.82558	.....
6	mar	6.18896	4.72991	5.39132	5.80510	.....
7	apr	6.00746	4.55589	5.08542	5.73148	.....
8	may	4.41770	3.33148	3.83660	4.20117	.....
9	jun	1.96810	1.12283	1.59684	1.64094	.....
10	jul	0.43582	0.13976	0.30905	0.21496	.....
11	aug	0.03228	0.00236	0.01102	0.00472	.....
12	sep	0.00669	0.00000	0.00078	0.00000	.....

*snow water equivalent (in):*

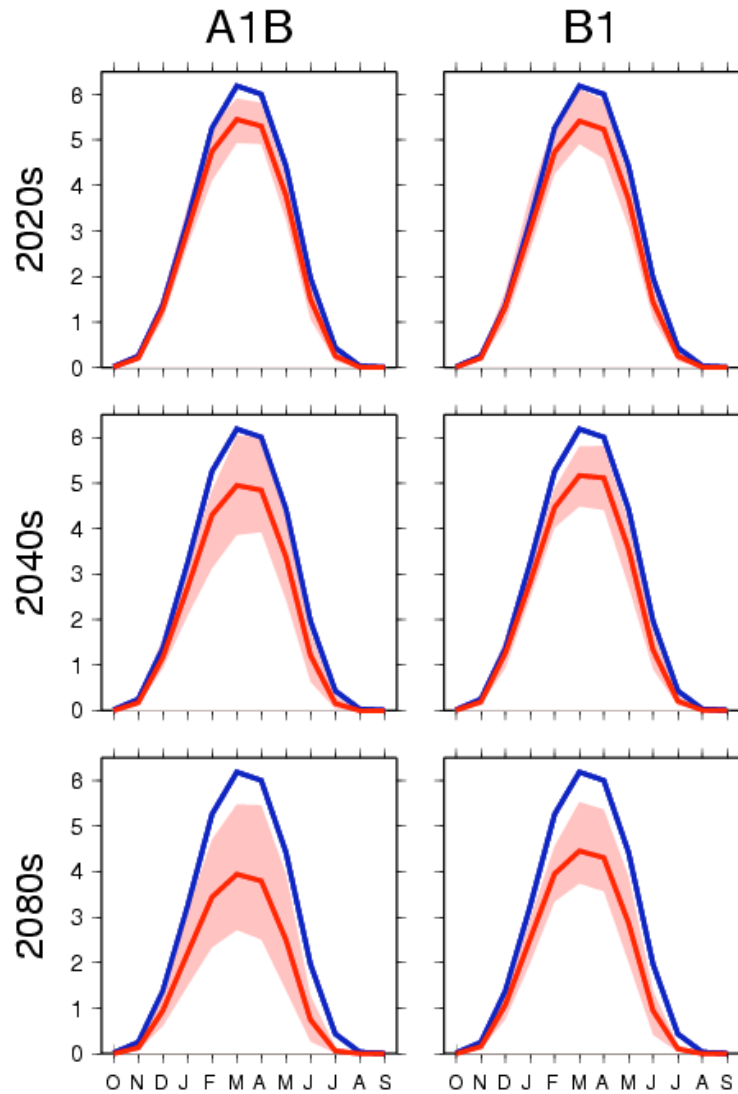


Figure 5 – Example of summary plot for SWE for the basin that drains into the Columbia River at The Dalles, OR (#4030). (Note figure will be updated as runs are completed)

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).

### 5.3 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.

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 4, and further information can be obtained from the ESRI help website (<http://webhelp.esri.com>, search for: “ESRI ASCII Raster format”). Figure 4 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).

Table 4 – 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.

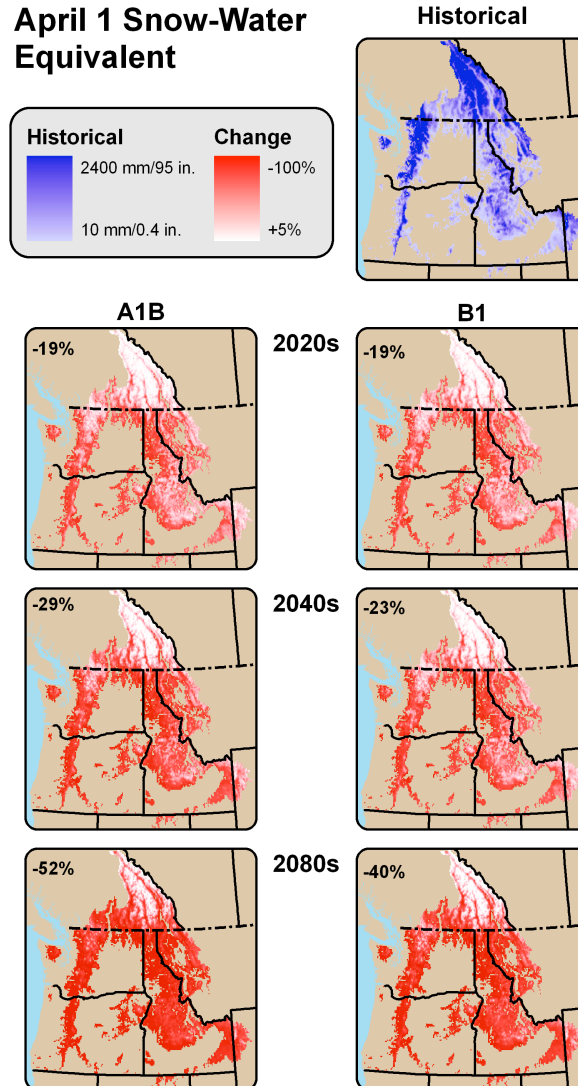


Figure 4 – Long-term mean of April 1 SWE for historic and six composite delta scenarios.

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.

#### 5.4 Reservoir Model Inputs

Bias corrected inflows to support two existing reservoir simulation models are supported in the scope of work for the current study. These models are the basin-wide

HYDSIM and GENESYS models, which are used by the BPA and Northwest Power and Conservation Council (NWPCC 2005) respectively for mainstem studies in the Columbia basin. These data are provided, in an agreed upon format, via an ftp site linked to the study web site ([http://www.hydro.washington.edu/2860/products/reservoir\\_model/](http://www.hydro.washington.edu/2860/products/reservoir_model/)). Data for each model and scenario are stored in a unique directory on the ftp site in ascii format. Naturalized flow products from specific sites were also used to provide naturalized inflows at model nodes needed to run the USBR MODSIM reservoir model for the Snake River basin (Labadie 2007).

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