RECLAMATION

Managing Water in the West

Hood River Basin Study:

Distributed Hydrology Soil and Vegetation Model Technical Memorandum

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region
Pacific Northwest Regional Office
Boise, Idaho

April 2014

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1.0 INTRODUCTION

The Hood River basin (Basin) is located in northwestern Oregon, and drains predominantly northwards directly into the Columbia River (Figure 1). The Basin is slightly more than 480 square miles (mi^2), and is wholly located within Climate Division 6 - North Central Oregon as designated by the National Climatic Data Center (Taylor 2014). Situated on the eastern flanks of the Cascade Mountains, the climate of the Basin is somewhat transitional. Moist air from the Pacific Ocean undergoes orographic lifting as it encounters the high elevations along the western and southern boundaries of the Basin, resulting in more precipitation in these regions (Figure 2). Conversely, as the moisture-deficient air descends and warms, it re-absorbs moisture from the land surface, leading to more arid conditions along the eastern and northern regions of the Basin (Figure 2).

There are three primary forks to the mainstem Hood River: the West Fork Hood River, the Middle Fork Hood River, and the East Fork Hood River (Figure 1). The West Fork Hood River subbasin accounts for 30 percent of the total Basin area, but due largely to the orographic effect discussed above, contributes greater than 40 percent of natural flow through the mainstem Hood River. The Middle Fork and East Fork combine to form the East Fork Hood River subbasin, which accounts for approximately 45 percent of the total Basin area and natural flow through the mainstem Hood River. The headwaters of this subbasin are fed in part by the glaciers along the northern and eastern sides of Mount Hood. The remaining 25 percent of the Basin is located downstream of the confluences of the three forks, and contributes just 15 percent of the mainstem flow.

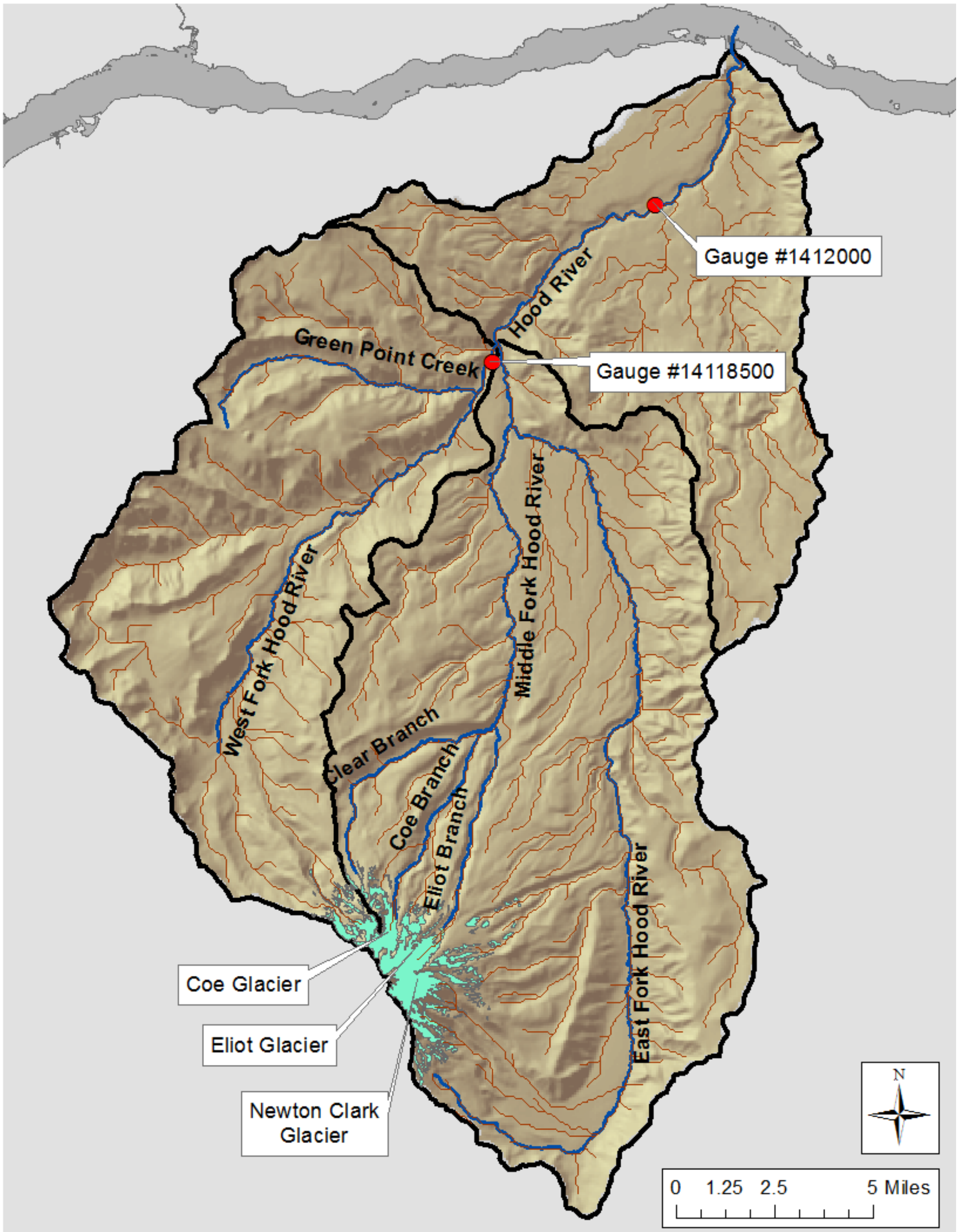


Figure 1. Shaded relief map of the Basin with key stream gage locations and glaciers.

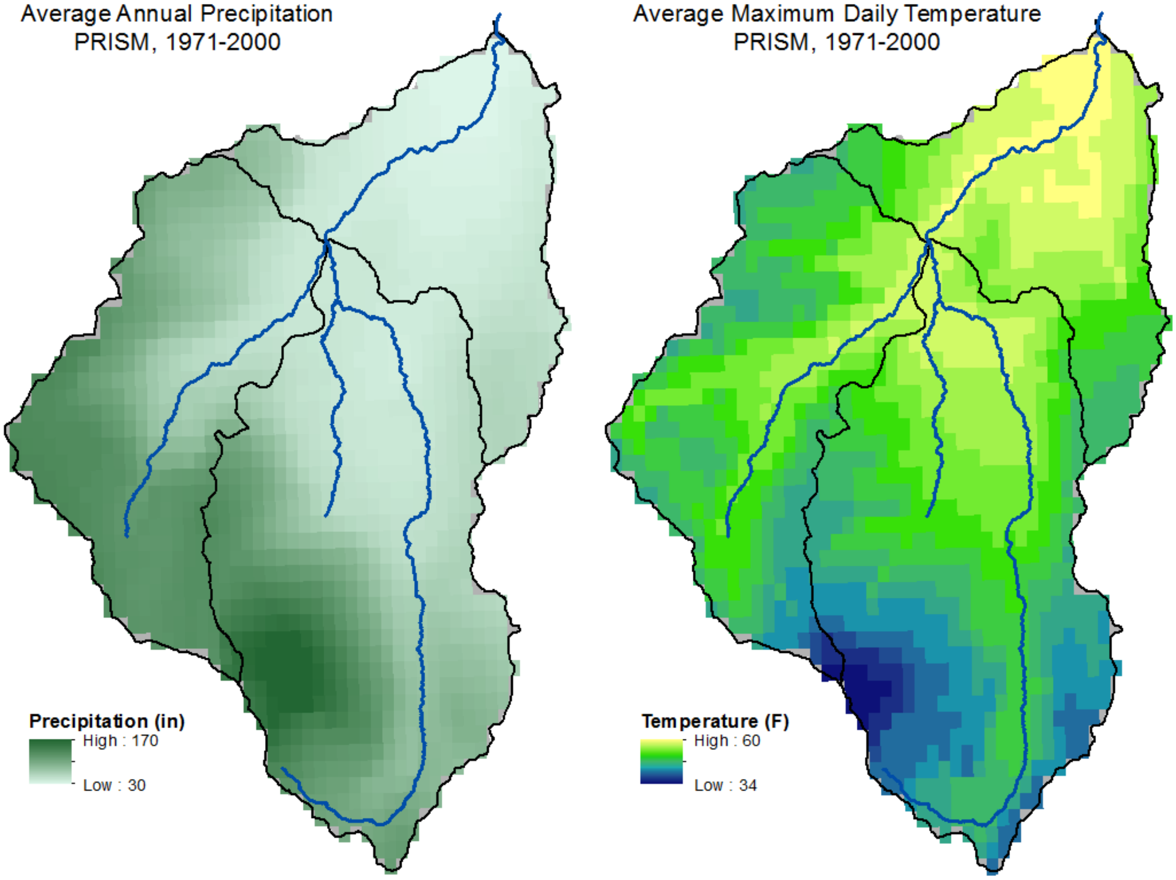


Figure 2. Parameter-elevation Regressions on Independent Slopes Model (PRISM) average annual precipitation (in inches) and average maximum daily temperature (in degrees Fahrenheit) for the Basin.

1.1 Purpose and Scope

The purpose of this technical memorandum is to document the development details of the physical runoff model constructed for simulating historical and projected future natural streamflows, as part of the Hood River Basin Study (Basin Study). In this technical memorandum, natural streamflows are considered those generated from watershed runoff in the absence of anthropogenic water uses (demands) and reservoir operations. The primary deliverables of the physical hydrologic modeling effort are natural streamflows at specific locations in the Basin where inputs to an associated water resources management (MODSIM) model are needed. The MODSIM model uses these flows to simulate potential impacts on the availability of water for agricultural, ecological, municipal, and energy needs from future climate change (Water Resources Modeling Technical Memorandum). In addition, the simulated historical and simulated future natural climate change flows were used to estimate the timing and quantities of water at many locations throughout the Basin to support stream habitat analyses, which are being conducted by Normandau Associates, Incorporated. The MODSIM results will help develop adaptation and mitigation strategies, which will be reported in the Basin Study Report.

2.0 MODEL DESCRIPTION

Reclamation collaborated with Watershed Professionals Network (WPN) and the University of Washington (UW) to obtain a Distributed Hydrology Soil Vegetation Model (DHSVM) for the entire Basin (at 90-meter resolution and 3 hour timesteps). The DHSVM model was calibrated to historically observed flows to estimate mean daily streamflow as part of the Instream Flow Incremental Methodology (IFIM) study being conducted for the Middle Fork Irrigation District (MFID).

At the time of the Basin Study, the DHSVM package utilized for this modeling effort was an unreleased version, as it incorporates dynamic glacier modeling code recently developed by the University of British Columbia (UBC) in collaboration with UW (Naz et al. 2014), as well as the latest software patches (Chris Frans, personal communication, November 20, 2013). In addition to glacier dynamics, algorithms simulating the surface energy balance and heat conductance of debris layers on glacier surfaces were developed to accurately simulate ablation rates of glaciers with areas covered in debris. These algorithms follow the derivation of heat conductance of Reid and Brock (2010). Additional details on how glacier physics are modeled and incorporated into DHSVM can be found in Naz et al. (2014). This extension to DHSVM allowed for evaluation of the potential impacts of increasing temperatures due to future climate change on Mount Hood glaciers.

DHSVM is a physically based hydrologic modeling package that accounts for the effects of topography and spatially-varying (heterogeneous) soil and vegetation properties on surface water fluxes through a given watershed (Wigmosta et al. 1994, Lettenmaier 2014). DHSVM is forced or driven by gridded meteorological input data, namely air temperature and precipitation. Detailed descriptions of how physical watershed properties and processes, namely soil moisture, snow cover, evapotranspiration (ET), and runoff production, are represented in DHSVM are presented in the original paper by Wigmosta et al. (1994), as well as a more recently updated descriptive publication by Wigmosta et al. (2002).

General information on the DHSVM model structure, calibration, and validation are provided in the following sections. Due to the complexity of the DHSVM model, specifically the glacier extension, significant support was obtained from UW throughout this modeling effort. Inquiries regarding additional technical details not specified in this technical memorandum should be directed to the UW Ecohydrology Research Group in Seattle, Washington (Istanbulluoglu 2014).

2.1 Input Data

Several spatial input data sets were used to construct the DHSVM model. Information on the primary data sets used in this model is here, but for additional information on general DHSVM input data requirements, refer to Lettermaier (2014).

2.1.1 Meteorological Data

Spatially distributed meteorological data, such as precipitation, temperature, wind, humidity, and solar radiation data, were determined for the historical period using a number of methodologies. Initially, observations (2001-2011) from nine meteorological stations in the Basin (Figure 3) were used as inputs, and the model was calibrated to raw observed streamflows. However, simulated snow water equivalent (SWE) and base flows (low flows during the mid- to late-summer) were poorly correlated with observed values. Additional efforts were thus pursued to improve the model calibration.

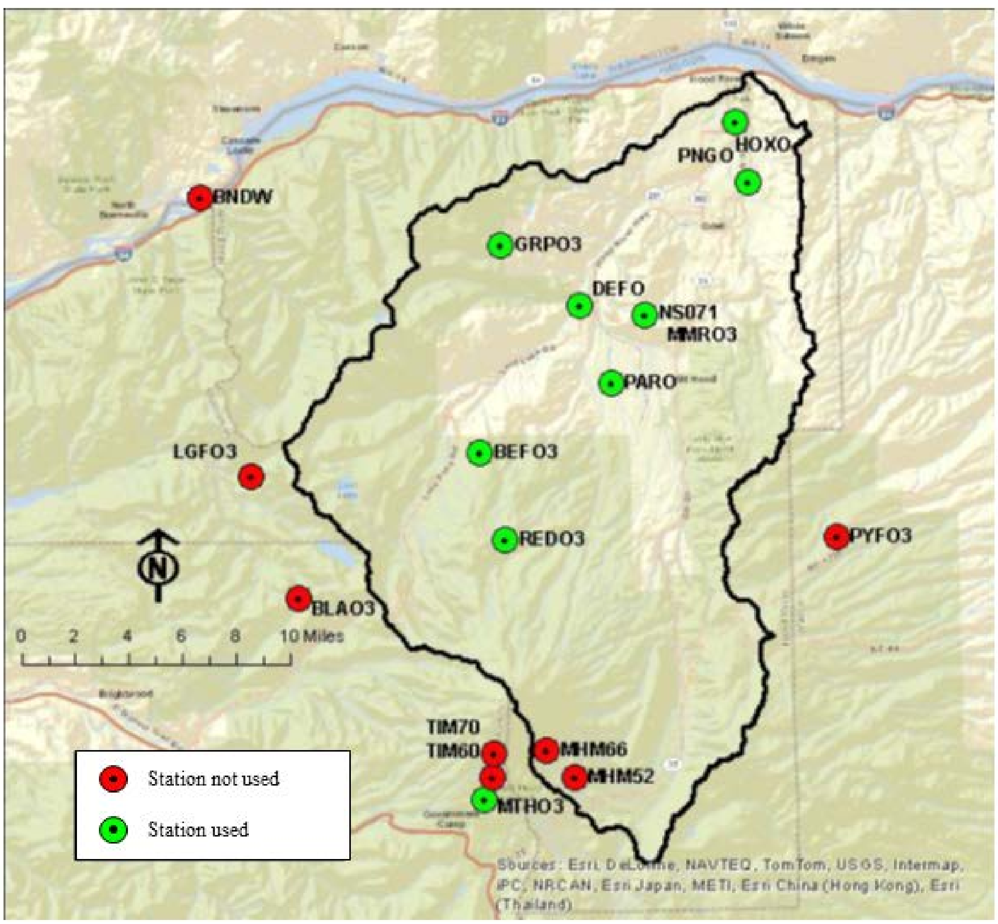


Figure 3. Locations of meteorological stations considered for the DHSVM model.

In an effort to improve the spatial distribution of meteorological data, the use of the Parameter-elevation Regressions on Independent Slopes Model (PRISM) developed by Oregon State University (PRISM Climate Group 2014) was explored. This statistically-based method translates point measurements of meteorological data into spatially distributed (gridded) estimates (Figure 2) by accounting for a suite of local and regional climatological and geographical factors. However, upon incorporating the PRISM data into the DHSVM model, it was found that minimum temperatures in the Basin were not accurately estimated. This created issues with the heat flux-dependent snowmelt and runoff patterns.

Additionally, the glacier extension was unable to accurately simulate historical observations of Mount Hood glacier dynamics using the aforementioned meteorological data sets (Frans, personal communication, January 22, 2014). To address all of the above mentioned issues affecting model performance, UW undertook a rigorous approach to produce gridded historical meteorological records, back-extended from 2000 to 1915, using the methodologies outlined in Hamlet and Lettenmaier (2005). Subsequent model calibration provided acceptable fits to observed SWE, base flows, and glacier dynamics (Section 2.2).

For details on the final meteorological inputs, specifically how they were adjusted for each climate change scenario, please refer to the accompanying Climate Change Technical Memorandum (2014).

2.1.2 Land Cover and Vegetation

Data from the 2006 National Land Cover Database (NLCD) and from the 2001 NLCD were used to classify land cover and vegetation types in the Basin. The final classification scheme resulted in 19 spatially distributed classes, ranging from open water to forest and shrub land. Figure 4 displays this classification scheme, simplified for visual display.

2.1.3 Soil Types and Depths

Soil survey data from the Natural Resource Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database were used to map soil types and depths across non-federal lands in the Basin, while Soil Resource Inventory (SRI) data were used to map this information across U.S. Forest Service lands. A total of 18 unique soil types were identified in the Basin. Figure 4 displays this classification scheme, simplified for visual display. Physical properties of these soils were provided by the associated data set (SSURGO or SRI). However, during the calibration process, parameters for the silty loam class were adjusted to values deemed more representative of the Basin.

Soil depths provided by the data sets generally ranged between 1 and 4 meters throughout the Basin. For areas where depth was unknown, interpolation between areas with known depths was utilized. During the calibration process, a uniform depth was applied across the Basin.

This was increased from an initial depth of 2 meters to a final depth of 4 meters.

2.1.4 Elevation

Digital elevation model (DEM) data at a 30-meter resolution were obtained from the U.S. Geological Survey (USGS). The DEM data were resampled to a 90-meter resolution to match the resolution of other spatial data sets. Additionally, the DEM was analyzed for erroneous sinks (i.e., modeled local depressions not representative of the ground surface), and a geoprocessing filling routine was employed to correct these issues to ensure that modeled surface runoff would drain in an appropriate downstream direction. The final DEM is shown in Figure 4.

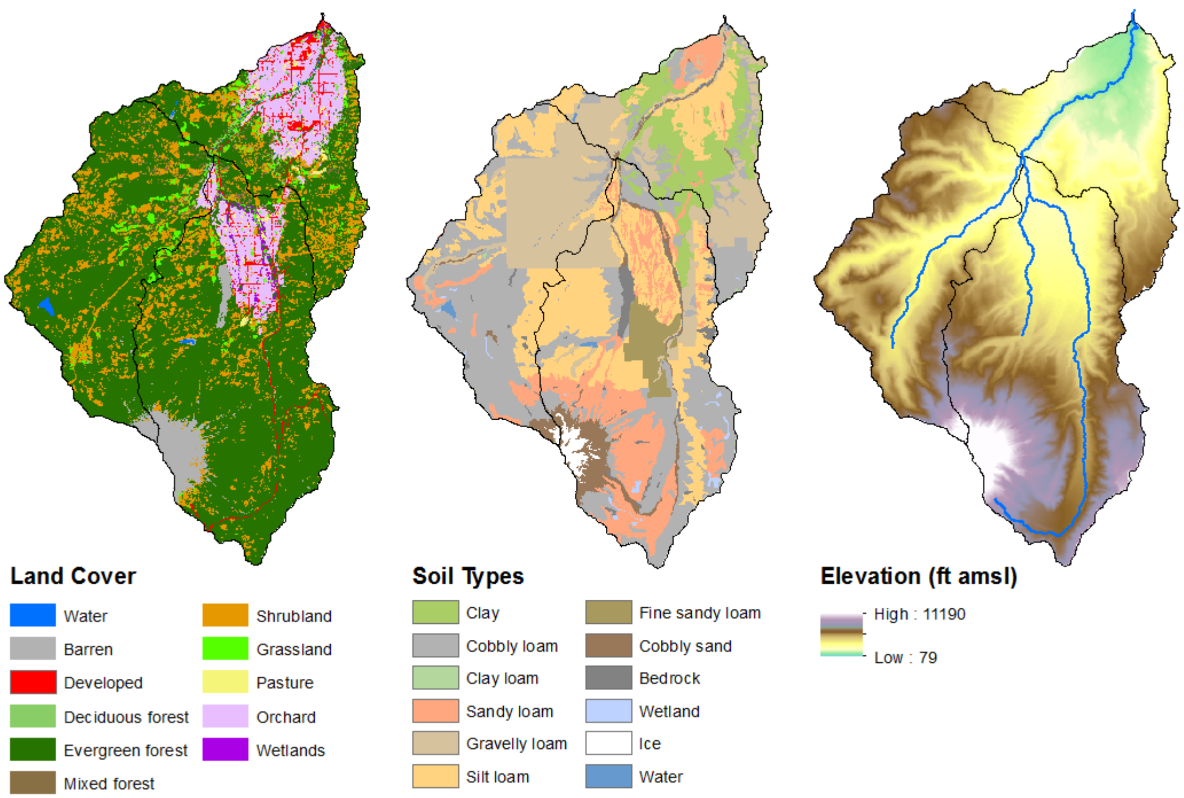


Figure 4. Spatial land cover, soil, and elevation data sets used to physically characterize the Basin for the DHSVM model.

2.1.5 Other Processed Data

DHSVM also requires a stream network for aggregating and routing modeled runoff at selected locations. WPN generated the stream network for the Basin using the DEM in conjunction with DHSVM-provided geoprocessing tools. Additionally, terrain shading and sky view of each model grid cell were generated by WPN via DHSVM-provided geoprocessing tools to incorporate topographically-specific incoming solar radiation effects on runoff production (Lettermaier 2014).

2.1.6 Glacier Characteristics

The glacier extension integrated into DHSVM requires subglacial topography, a spatial distribution of ice thickness (to initialize the model), and the spatial distribution of the thickness of debris on glacier surfaces as inputs. The subglacial topography (the elevation of the land surface beneath the ice masses) was estimated using the surface DEM, mass balance fields, observed thinning rates, and a bed stress model (Clarke et al. 2012). The distribution of ice thicknesses used to initialize the model was estimated by running the glacier dynamics model offline (i.e., without the DHSVM hydrology components) for 1000 years with a prescribed annual mass balance rate. The prescribed mass balance rate was adjusted so that the extent of the steady glacier masses (end of 1000 year simulation) matched the historical estimate of glacier areas provided in Jackson and Fountain (2007). This method of “spinning up” the glacier ice masses with the glacier dynamics model ensured that the initial state of the ice masses in the full hydrologic simulation was mechanistically stable, avoiding transient adjustments early in the simulation.

The ablation areas of Eliot and Coe glaciers (Figure 1) are partially covered with debris. The debris consists of material that is deposited on the glacier surface from the erosion of adjacent slopes and englacial material deposited on the surface through melting of ice. While thin debris cover on glaciers can reduce albedo and increase rates of melting, thicker debris cover acts as an insulator, storing and conducting heat to the glacier ice, and retards rates of melting as compared with debris free areas. The thickness of debris on Eliot glacier was estimated by interpolating (bilinear method) the point measurements reported in Appendix C of Jackson (2007). The longitudinal gradient in debris thickness derived from these measurements and aerial images were used to estimate the distribution of debris thickness on Coe glacier.

2.2 Model Calibration

Calibration of the DHSVM model was an iterative process, initially performed via coordination between WPN (2012) and UW, and finalized by UW in 2013. Because this process was highly complex, involving the adjustment of many model parameters and producing many interim versions of the model that required validation by multiple parties, this technical memorandum only focuses on the key features and results of the model calibration. For additional details regarding general DHSVM calibration, please visit the DHSVM website (Lettenmaier 2014). For more technical details specific to calibration of the glacier parameters, please contact the UW Ecohydrology Research Group in Seattle, Washington (Istanbulluoglu 2014).

A multi-objective approach was used to calibrate the DHSVM model. The parameters utilized in calibration include temperature and precipitation lapse rates, soil hydraulic properties, glacier ice albedo, and the maximum snow albedo used in snow albedo decay curves. First, the model was calibrated to match estimated naturalized discharge volumes along the mainstem at the Hood River at Tucker Bridge USGS gaging site and raw flow measured at the West Fork Hood River near Dee USGS gaging site. These calibration efforts emphasized the performance of the simulation of low flows. Additionally, the model was calibrated to capture the trajectory of glacier area change documented by Jackson and Fountain (2007). Parameters used in the simulation of the surface energy balance algorithms of debris covered glaciers were calibrated to match point ablation measurements reported in Jackson (2007). Additional details regarding model calibration are provided in the following sections.

2.2.1 Glacier Characteristics

Historical glacier observations from Jackson and Fountain (2007) were utilized in the calibration of the processes that control glacier mass accumulation, ablation and, ultimately, rates of recession. The glacier dynamics model is grounded in physical algorithms derived from Glen’s Flow Law. Constants and parameters required for these algorithms were taken from glaciology literature (Cuffey and Patterson 2010) and were not modified during calibration. However, parameters governing surface accumulation and ablation rates were modified to match measured rates of ablation and areal recession. These calibrated parameters include the glacier surface albedo, maximum snow albedo, precipitation and temperature lapse rates, and the thermal conductivity and surface albedo of debris on glacier surfaces.

Refer to Naz et al. (2014) and the UW Ecohydrology Research Group in Seattle, Washington (Istanbulluoglu 2014) for additional details on calibrating the glacier extension of DHSVM.

2.2.2 Snowpack

In addition to streamflow, the calibration process included the analysis of simulated historical versus observed snow water equivalent (SWE) and cumulative precipitation at three NRCS SNOTEL (snow telemetry) stations in or near the Basin. These SNOTEL locations are listed in Table 1 and displayed in Figure 3. As shown, each station is situated at a different elevation, with approximately 1,000 vertical feet separating each from its nearest vertical neighbor. Although the Mount Hood Test Site is located outside of the Basin, this location was included for calibration because it represents the highest elevation range of any nearby SNOTEL station.

Table 1. NRCS SNOTEL stations used in the DHSVM model.

Name	Latitude, Longitude (NAD 1983)	Elevation (feet above mean sea level)	Period of record	Comments
Mount Hood Test Site (MTHO3)	45.32, -121.72	5370	07/1980 - present	Located on the south/southwest side of Mount Hood, outside of the Basin
Red Hill (REDO3)	45.46, -121.70	4410	10/1978 – present	Located in the Middle Fork Hood River drainage
Greenpoint (GRPO3)	45.62, -121.70	3310	10/1978 - present	Located in the lower West Fork Hood River drainage

Calibrated cumulative precipitation and SWE values are plotted against the corresponding observed values in Figure 5 and Figure 6, respectively. Overall, the simulated historical precipitation agrees with observations; however, the DHSVM model consistently under-simulates the annual precipitation peak at the Mount Hood Test Site by 10 to 30 percent. This under-simulation contributes to the discrepancies between simulated historical and observed SWE at this location. Although, considering that the modeled SWE values are less than 30 percent of those measured, one or more additional factors may be involved.

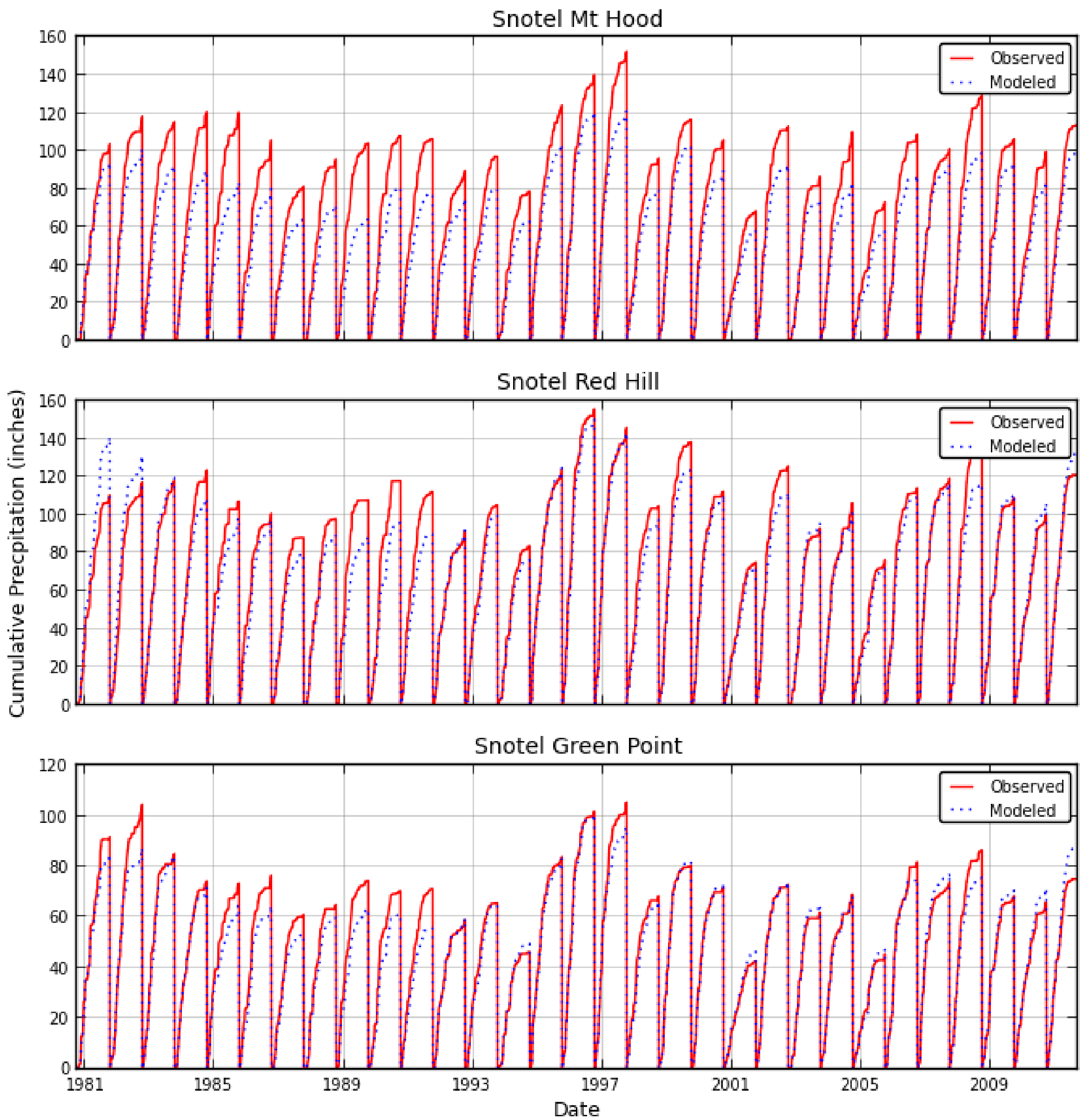


Figure 5. Calibrated cumulative precipitation results for the DHSVM model.

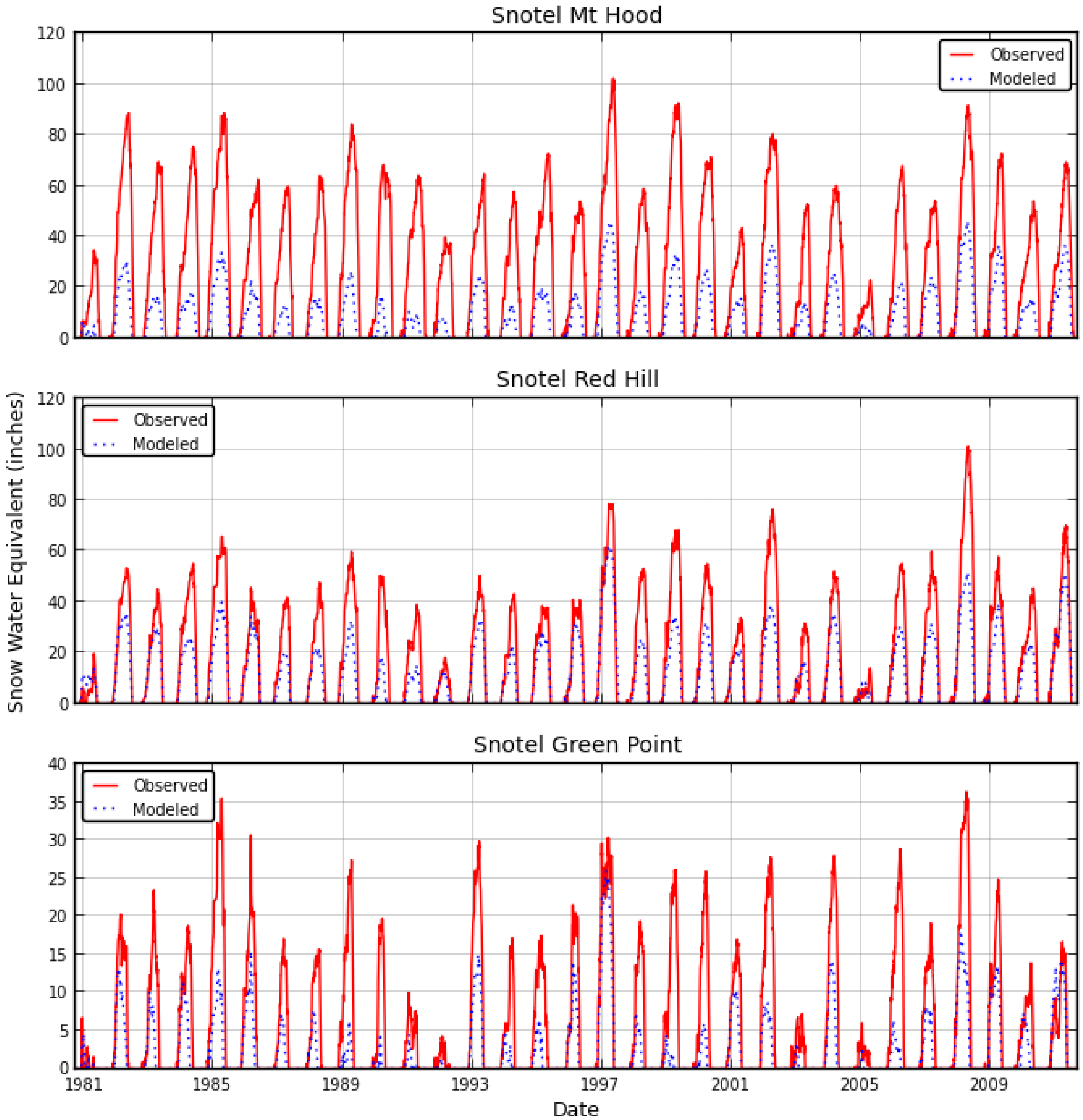


Figure 6. Calibrated snow water equivalent (SWE) results for the DHSVM model.

For example, the simulated historical temperatures could be higher than those observed and/or simulated historical snow melt could be unrealistically productive. If the temperatures in the DHSVM model are too high, then more precipitation may be typed as rain instead of snow. This precipitation shift could not only hinder snowpack accumulation but also increase snow melt via rain-on-snow energy transfer. Additionally, if the physical energy balance controlling snowpack ripeness, which describes how close the snowpack is to melting, is not modeled accurately, then snow melt could be simulated to commence too soon and/or be too persistent. In complex terrain like that found on and near Mount Hood, accurate modeling of snowpack ripeness can be very difficult to achieve. Lastly, because actual SNOTEL sites have been cleared of over-story, whereas they are tree-covered in the DHSVM model, the SWE measurements in Figure 6 may be upwardly biased as open areas more readily accumulate snow. Thus, future efforts should consider removing the tree cover from the DHSVM model grid cells corresponding to SNOTEL sites and re-evaluating simulated historical versus observed SWE.

The Mount Hood Test Site, in addition to being outside of the Basin, is located on a south-facing slope. Thus, if the dampening impacts of cloud cover on radiative input to snowpack are under-represented in the DHSVM model, then snow melt at this location may be over-simulated because of the aspect. Because the Basin has predominantly northern exposure, aspect-related over-simulation of melt rates would not be expected to systematically bias simulated historical SWE values across the DHSVM model domain.

The results for the Red Hill SNOTEL location are likely more applicable because this site represents a relatively central location in the Basin (Figure 3). As shown in Figure 5, the simulated historical cumulative precipitation curves are quality analogs of the observed curves. The simulated historical SWE values, shown in Figure 6, are generally lower than those observed, but capture the observed year-to-year trends (average versus wet/dry years) very well. Additionally, simulated historical SWE values appear to reasonably approximate observed values in many cases, namely during dry years. These results are more important in terms of climate change than good agreement during wet years because future climate change conditions are expected to decrease snowpack in the Basin (Section 4.2). Similar results are shown for the Greenpoint SNOTEL location (Figure 5 and Figure 6).

Given that observed SWE is generally underestimated at the Red Hill and Greenpoint SNOTEL locations (but considering the good agreements with cumulative precipitation), the results for these locations do support the aforementioned idea that the observed SWE values could be upwardly biased because of a lack of tree cover. One of the primary calibration parameters in this study was the air temperature lapse rate, which describes how temperature decreases with elevation. In addition to developing robust historical meteorological forcings, UW devoted significant focus to the temperature lapse rate to accurately simulate precipitation typing and snow melt. Instead of applying a constant lapse rate across the full spatial and temporal domain of the DHSVM model (which is the standard DHSVM approach), UW generated location- and time-dependent lapse rates (Chris Frans, personal communication, January. 23, 2014). Thus, although discrepancies from observed SWE are clearly evident, due diligence was applied to modeling snowpack in the Basin. As mentioned above, future efforts should consider modifying the NLCD classifications at the SNOTEL sites to be more representative of their actual locations. This would enable a more direct comparison between simulated historical and observed SWE, but would maintain the integrity of the existing calibration.

2.2.3 Streamflow

The primary streamflow calibration locations were Hood River at Tucker Bridge (USGS #14120000) and West Fork Hood River near Dee (USGS #14118500), where the USGS has continuously operated stream gages for the last several decades (Figure 1). The Hood River at Tucker Bridge gage has an official, continuous period of record from January 1965 to present, and partial records dating back to October 1897. The West Fork Hood River near Dee gage has an official, continuous record from October 1932 to present. Because DHSVM simulates natural flows, the observed streamflows for the Hood River at Tucker Bridge gage, which is located downstream of nearly all water uses in the Basin (WPN 2013a), were naturalized (all upstream diversions added to observed flows) by WPN according to the procedures detailed in the Hood River Basin Water Use Assessment. However, because minimal water use occurs upstream of the West Fork Hood River near Dee gage, unadjusted observations were used to calibrate the DHSVM model along the West Fork Hood River. Additional observed stream and canal flow data, as well as reservoir storage and release estimates, were incorporated into the MODSIM effort, described in the accompanying Water Resources Modeling Technical Memorandum.

Figure 7 displays the calibrated streamflows for the climatically variable period from 2001 to 2011. For both locations, the DHSVM model produces flows that are statistically valid simulations of the naturalized or observed flows based on Nash-Sutcliffe Efficiency (NSE) values greater than 0.5 (Nash and Sutcliffe 1970).

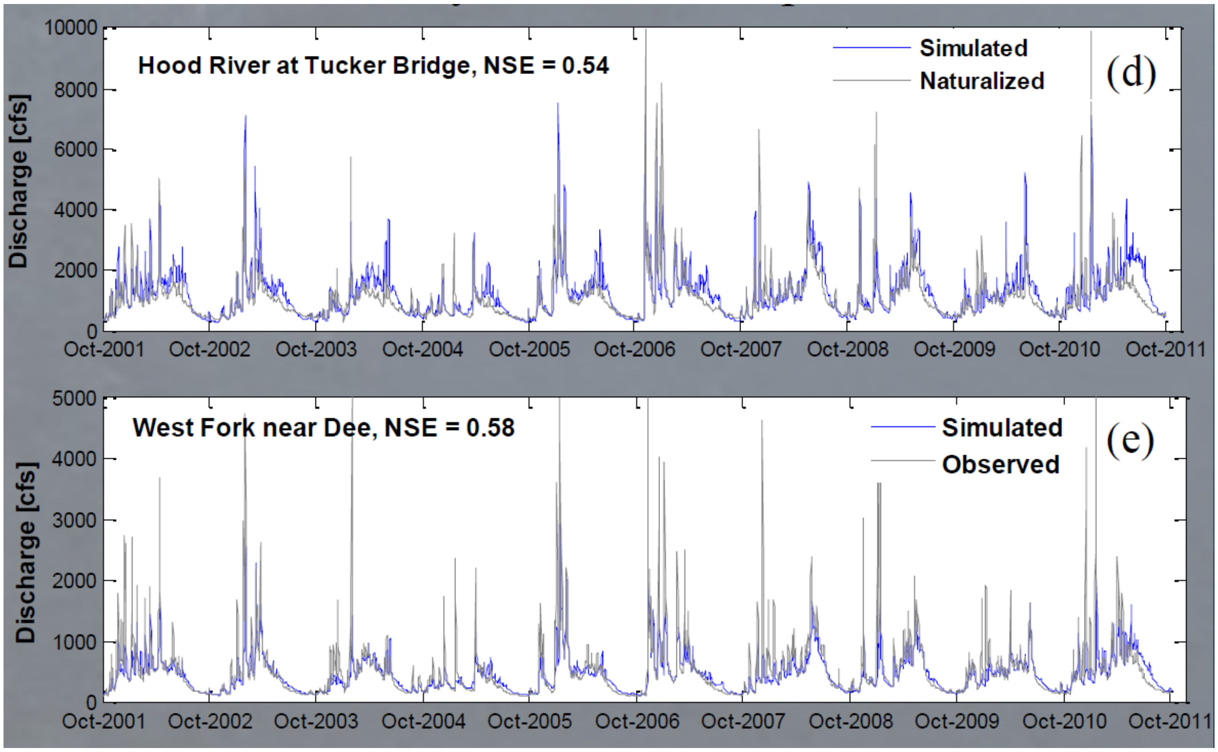


Figure 7. Calibrated streamflow results for the DHSVM model (Frans, C., unpublished manuscript, 2014).

3.0 HISTORICAL RESULTS

Because DHSVM is a physically-based model that emphasizes the effects of land cover, specifically soil and vegetation, on the translation of meteorological inputs (i.e., precipitation, temperature, solar radiation, etc.) into streamflow, model output options are wide-ranging. For a complete description of the available DHSVM outputs, please refer to the DHSVM website (Lettenmaier 2014), as well as Naz et al. (2014) for glacier-specific outputs. For the purposes of this technical memorandum, the focus was placed on a few key outputs relevant to streamflow, snowpack, and the glaciers forming the headwaters of the Middle Fork Hood River and East Fork Hood River. A discussion on how each pertains to describing the potential effects of climate change on water resources in the Basin can be found in the Section 4.0.

By default, DHSVM outputs variables in aggregate form, or areal-averages across the model domain. Because the potential impacts of climate change were assessed on a relative basis, this format was appropriate for most of the key output variables. However, streamflow and glacier melt outputs were refined to represent values at specific locations (i.e., stream reaches) that will be discussed below.

3.1 Glacial Characteristics

The historical meteorological forcings used as input to the DHSVM model were extended from 2000 back to 1915 for model calibration. This was primarily to enable comparisons between simulated historical and observed glacier characteristics (Chris Frans, personal communication, September 23, 2013), which began in the early 1900s (Jackson and Fountain 2007). Figure 8 displays simulated Basin glacier volume and areal extent results for water years 1920 through 2009. Results for water years 1916 through 1919 are omitted because the glacier extension required a few simulation years to stabilize (Chris Frans, personal communication, September 23, 2013). The volume and extent data are relative to the simulated values for October 1, 1919. Following an initial, relatively sharp decline, the DHSVM model simulates a steady increase in glacier volume between the early 1940s and the mid-1980s. Even though the DHSVM model simulates a gradual decline during the last 20 years, the glacier volume at the end of 2009 remains effectively unchanged from 90 years prior. In contrast, the DHSVM model simulates glacier areal extent to generally decline throughout the full period, by more than 20 percent by the end of 2009.

These simulated patterns of glacier volume and area are both consistent with historical observations (Jackson and Fountain 2007) and are reasonable considering the physics of glacier dynamics. Jackson and Fountain (2007) reconstructed similar patterns of ice covered area and volume (noted by ice thickness measurements on Eliot glacier) from historical aerial photography and field measurements. It is not unusual for changes in glacier volume and extent to be in opposing directions (Chris Frans, personal communication, March 19, 2014). Glaciers can be divided into two zones, the accumulation zone and the ablation zone. In the accumulation zone, net mass changes on the annual scale are positive, whereas the changes are negative in the ablation zone. The accumulation zone is generally greater in area and volume than the ablation zone. Changes in glacier volume are largely controlled by the mass of the accumulation zone and will reflect short-term mass gains (i.e., during wet periods). Glacier area largely reflects changes of the extent of the lower reaches of the glaciers and will respond more slowly to volume changes. Much of the year-to-year variability in volume is not seen in area as it is filtered out through the slow dynamic flow of ice to lower elevations. Thus, the areal extent of a glacier is more an expression of long-term changes, whereas glacier volume will reflect more short-term changes due to inter-annual and decadal variability.

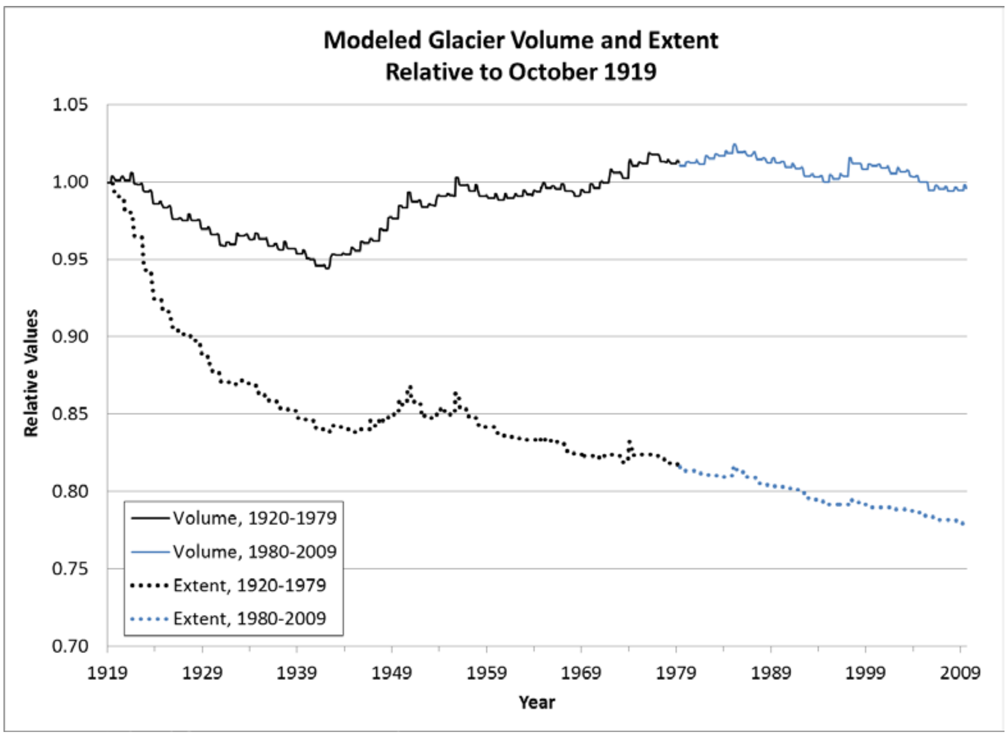


Figure 8. Simulated historical glacier characteristics from water years 1920 through 2009.

3.2 Snowpack

In contrast to the observed streamflow and glacier characteristics data, observed SWE data from the three SNOTEL stations used in the DHSVM modeling effort (Table 1) only date back to 1980. Thus, the snowpack parameters of the DHSVM model were calibrated to the 1980 to 2009 period. However, because comprehensive observed data rarely encompasses the full period of interest, common practice in hydrologic modeling is to apply model parameters determined for an appropriate calibration period to antecedent and/or subsequent time periods. Following this methodology and using observed streamflow data to constrain the results, snowpack information was simulated back to 1915 using the back-extended meteorological data.

Figure 9 illustrates the simulated Basin-wide snow areal extent on April 1st of every year from 1920 through 2009. Although the last four years of data suggest a temporary increase in snowpack, the overall historical trend is decreasing. The plotted linear trend indicates a decrease of 0.15 percent per year, or approximately 5 percent every 30 years. The results plotted in Figure 10 offer additional evidence for the apparent decreasing snowpack in the Basin in that the monthly average Basin-wide snow extents for the most recent 30 year period are lower than those of the preceding 30 year periods in nearly every month. In addition, the changing conditions suggested in Figure 10 are consistent with the anticipated impacts of future climate change on the Basin, including a shift in the timing of peak runoff to earlier in the water year, and declining summer water supplies.

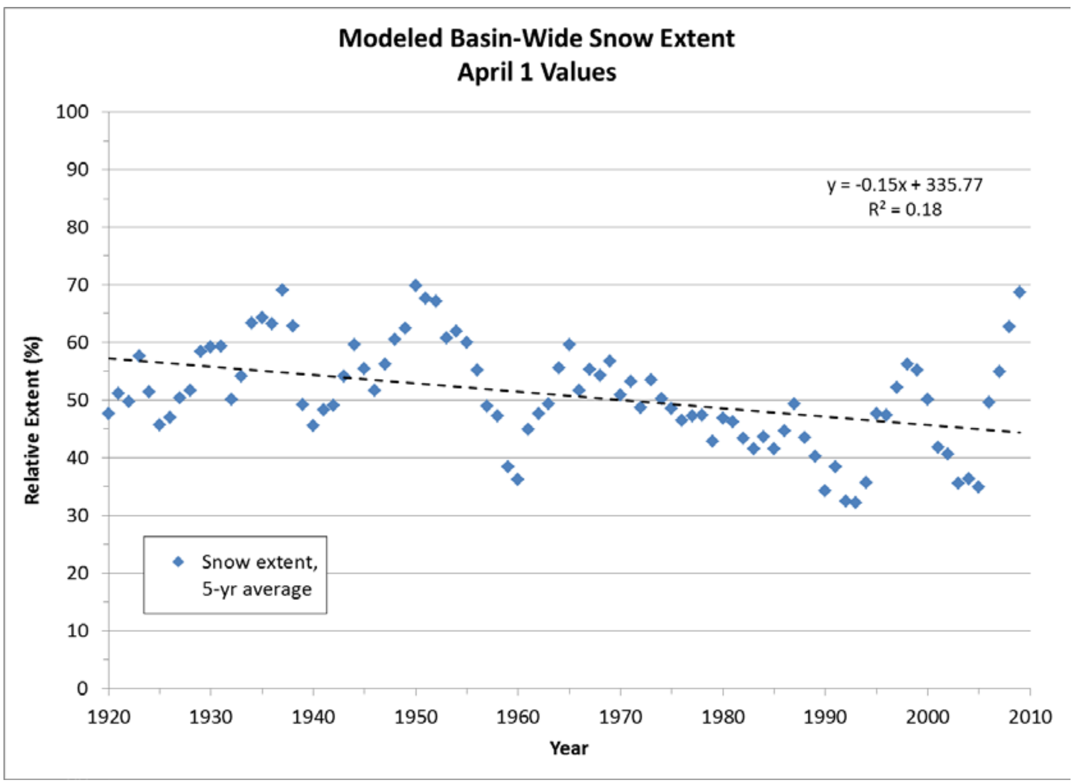


Figure 9. Simulated historical April 1 snow extent values, averaged across the Basin.

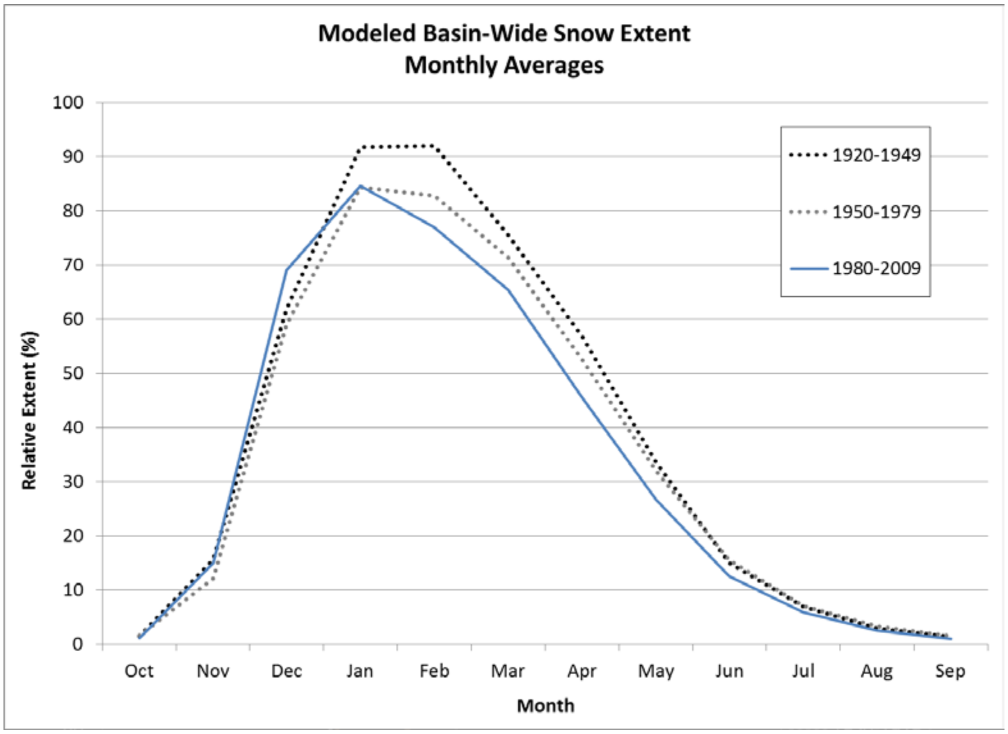


Figure 10. Simulated historical monthly snow extent values, averaged across the Basin.

3.3 Streamflow

A total of 42 unique locations across the Basin were specified for generating surface runoff accumulation (or streamflow) outputs. These locations are listed in Table 2 and are displayed in Figure 11.

Table 2. Stream reaches specified for DHSVM model output. Headwater locations are notated in bold.

Name	Subbasin	Location
HoodRvAtMouth	Hood River	Hood River at mouth of Basin
HoodRvAtPowerdale	Hood River	Hood River at Powerdale Dam
HoodRvAtTucker	Hood River	Hood River at Tucker Bridge, USGS gage 14120000
IndianCkAbvMouth	Hood River	Indian Creek above diversions
NealCkAtMouth	Hood River	Neal Creek at mouth
NealCkAbvWFNealCk	Hood River	Neal Creek above West Fork Neal Creek
WFNealCkAbvLateral	Hood River	West Fork Neal Creek above Neal Creek Lateral
OdellCkAtMouth	Hood River	Odell Creek at mouth

Name	Subbasin	Location
DitchCkAbvPower	Hood River	Ditch Creek above powerhouse intake
GreenPtLowRes	Hood River	Local inflows to Lower Green Point Reservoir
GreenPtUppRes	Hood River	Local inflows to Upper Green Point reservoir
PineCkAtMouth	Hood River	Pine Creek at mouth
WestFkNrDee	West Fork Hood River	West Fork Hood River near Dee, USGS gage 14118500
WestFkAbvGreenPt	West Fork Hood River	West Fork Hood River above Green Point Creek
WestFkAbvLakeBr	West Fork Hood River	West Fork Hood River above Lake Branch
DeadPtCkAtMouth	West Fork Hood River	Dead Point Creek at mouth
GreenPtCkBlwNGreen	West Fork Hood River	Green Point Creek below North Green Point Creek
NGreenPtCkAtStanley	West Fork Hood River	North Green Point Creek at Stanley-Smith Pipeline
LakeBrAtMouth	West Fork Hood River	Lake Branch at mouth
LakeBrBlwLost	West Fork Hood River	Lake Branch below Lost Lake
EastFkAbvWF	East Fork Hood River	East Fork Hood River above West Fork Hood River
EastFkAbvMF	East Fork Hood River	East Fork Hood River above Middle Fork Hood River
EastFkBlwWisehart	East Fork Hood River	East Fork Hood River below Wisehart Creek
EastFkBlwEvans	East Fork Hood River	East Fork Hood River below Evans Creek
EastFkAbvMain	East Fork Hood River	East Fork Hood River above Main Canal
EastFkAbvDog	East Fork Hood River	East Fork Hood River above Dog River
TroutCkAtMouth	East Fork Hood River	Trout Creek at mouth
WisehartCkAtMouth	East Fork Hood River	Wisehart Creek at mouth
EmilCkAtMouth	East Fork Hood River	Emil Creek at mouth
EvansCkAbvGriswell	East Fork Hood River	Evans Creek above Griswell Creek

Name	Subbasin	Location
GriswellCkAtMouth	East Fork Hood River	Griswell Creek at mouth
DogRvAtMouth	East Fork Hood River	Dog River at mouth
DogRvAbvPuppy	East Fork Hood River	Dog River above Puppy Creek
ColdSpringCkAtMouth	East Fork Hood River	Cold Spring Creek at mouth
MiddleFkAbvEF	East Fork Hood River	Middle Fork Hood River above East Fork Hood River
MiddleFkAbvTony	East Fork Hood River	Middle Fork Hood River above Tony Creek
MiddleFkAtRedHill	East Fork Hood River	Middle Fork Hood River at Red Hill Road
TonyCkAbvMouth	East Fork Hood River	Tony Creek above diversions
RogersCkAtMouth	East Fork Hood River	Rogers Creek at mouth
EliotBrAbvMouth	East Fork Hood River	Eliot Branch above diversions
CoeCkAbvMouth	East Fork Hood River	Coe Creek above diversions
ClearBrAtLaurance	East Fork Hood River	Local inflows to Laurance Lake

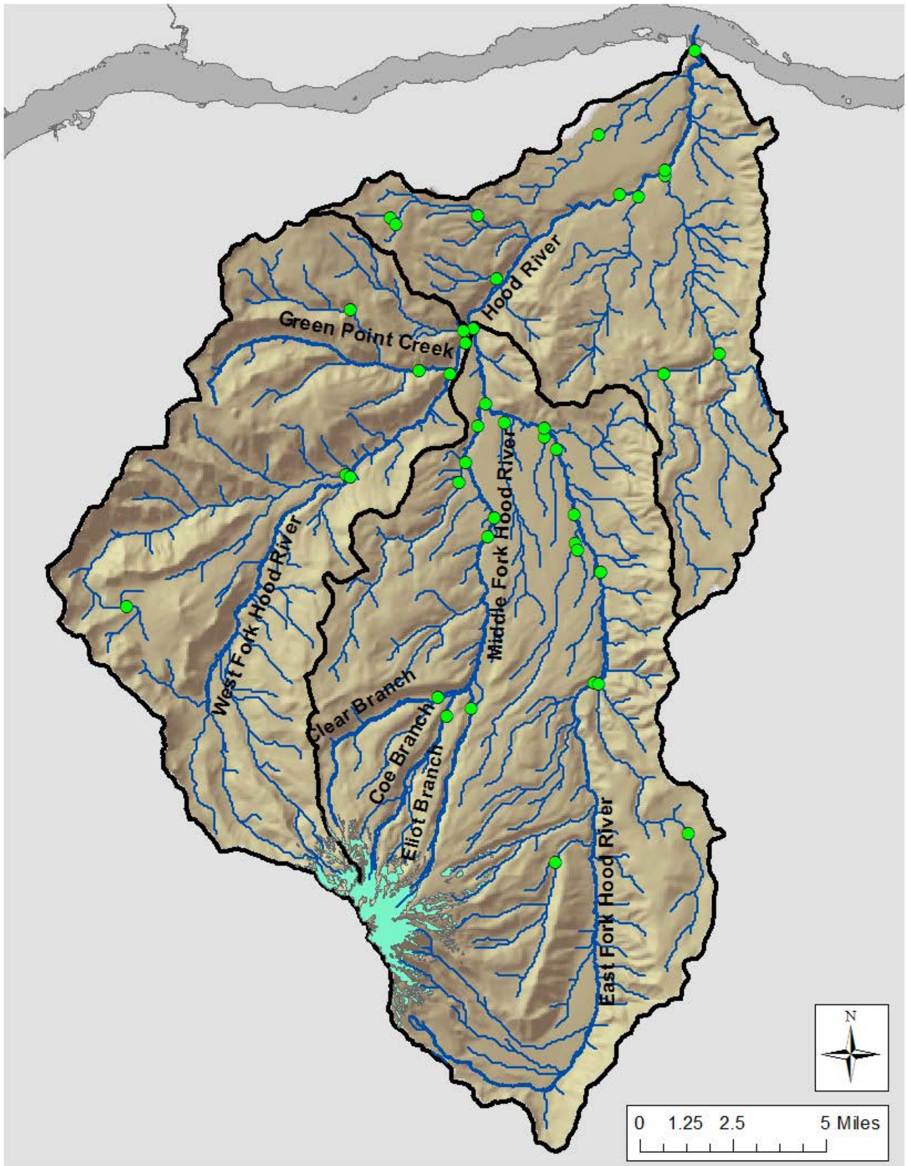


Figure 11. Locations specified for DHSVM model streamflow outputs.

Although total surface water runoff from the Basin could be generated at a single location at the mouth of the Hood River, this information would not be descriptive enough to inform the MODSIM model or any parallel studies being conducted by the Basin Study project partners. Further, calibration of the DHSVM model required looking at flows through locations where long-term stream gage data are available (Section 2.2.3). Additionally, given the non-uniform climate characteristics across the Basin (Section 1.0), flow locations were also chosen to, cumulatively, encompass the heterogeneity in surface runoff patterns. This approach allowed for comparisons to short-term stream gage records, statistical estimates of flow, and local and/or expert knowledge for investigating potential bias correction needs (discussed below).

With respect to describing flows in a manner suitable for the MODSIM model, each location in Table 2 can be classified as either of the following:

- Headwater
    - Locations upstream of all existing and potential diversions and reservoirs/lakes. The mouths of small tributaries were chosen if exact location(s) of diversions were not readily identified. Headwater locations are notated in bold in Table 2.
- Incremental
    - Locations downstream of one or more diversion, reservoir, and/or headwater location. Incremental locations allow calculation of local contributions to streamflow, which are the unaltered runoff originating from watershed areas where anthropogenic alterations exist.

The selection of some headwater locations was straightforward given the hydrography of the Basin, such as local inflows to Laurance Lake. However, identifying others was more difficult, such as Coe Creek above diversions. For these, the Hood River Basin Water Use Assessment was used in conjunction with points of diversion (POD) locations, obtained through the Oregon Water Resources Department (OWRD), to ensure the headwater locations were just upstream of all existing anthropogenic alterations.

The appropriate incremental locations were selected in a similar manner to headwater locations, but the selection process also accounted for minimum flow agreements, the needs of the IFIM study (summarized in the Basin Study Report), and specific key locations of interest to Reclamation stakeholders. Additional information can be found in the accompanying Water Resources Modeling Technical Memorandum.

To fully understand the potential impacts of climate change on surface water resources, and to fully evaluate potential mitigation and adaptation actions, modeled streamflows were needed at many locations across the Basin. Because only two long-term stream gages were available to calibrate to, as described in Section 2.2.3, statistical flow estimates at ungaged locations were also explored to constrain modeled flows.

Bias correction is a term used to describe when modeled outputs are adjusted without modifying model parameters. This technique has utility in instances where modifying model parameters to improve a specific model output may negatively impact other outputs. Additionally, as was the case during the DHSVM modeling effort, bias correction can be useful when there is a lack of physical data to justify modifying model parameters outside of generally acceptable ranges.

In 2009, the USGS published a report and associated data set detailing techniques to statistically estimate unregulated (i.e., natural) streamflows in Oregon (Risley et al. 2009). USGS statistical estimates of monthly flows were generated for every location listed in Table 2. The historically simulated flows at each location were then compared against the appropriate flow estimates.

Two examples of an approach used to compare simulated historical flows with the statistically estimated flows are provided below. Figure 12 displays a comparison plot for Green Point Creek. The gray shaded area represents the statistical range (10th to 90th percentiles) of monthly flows, and the black solid line illustrates the median monthly simulated historical flows. As shown, the simulated historical flows appear to be reasonably well centered within the statistical range, implying that bias corrections of the DHSVM model flows are unnecessary. In contrast, Figure 13 might suggest that simulated historical flows for the East Fork Hood River are slightly low when compared to the statistical range. However, inspection of the statistical range raises some doubt as to the applicability of the USGS technique to this location, namely the unexpected peak in August and the large range of values (the scale of which overwhelms the simulated historical average monthly hydrograph).

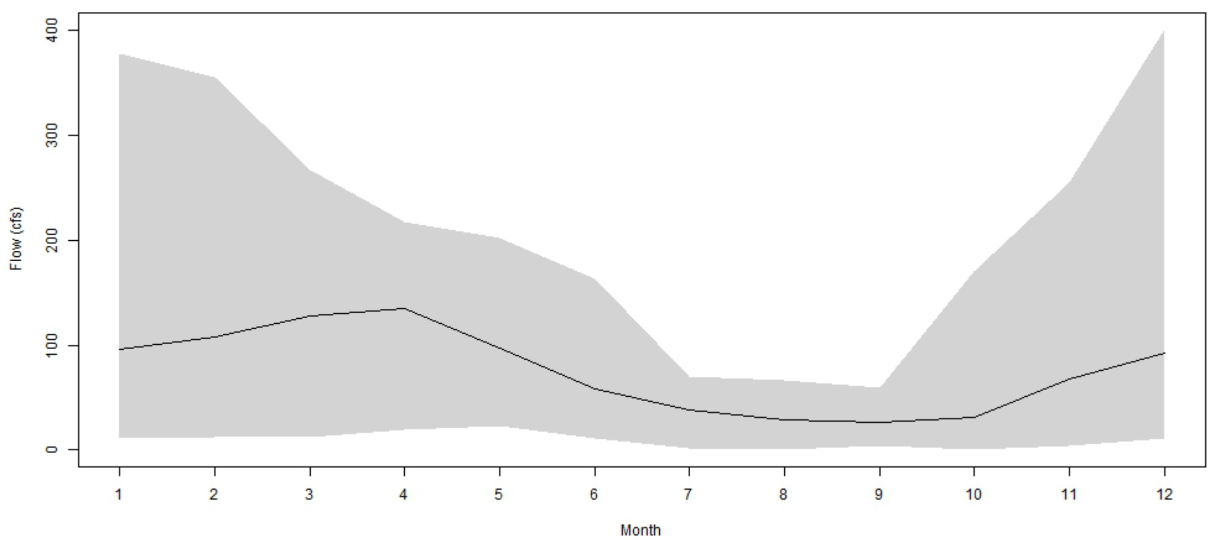


Figure 12. Comparison between monthly median simulated historical flows (solid black line) and the range between the 10th and 90th percentiles of the USGS regional regression method (gray shading) for Green Point Creek.

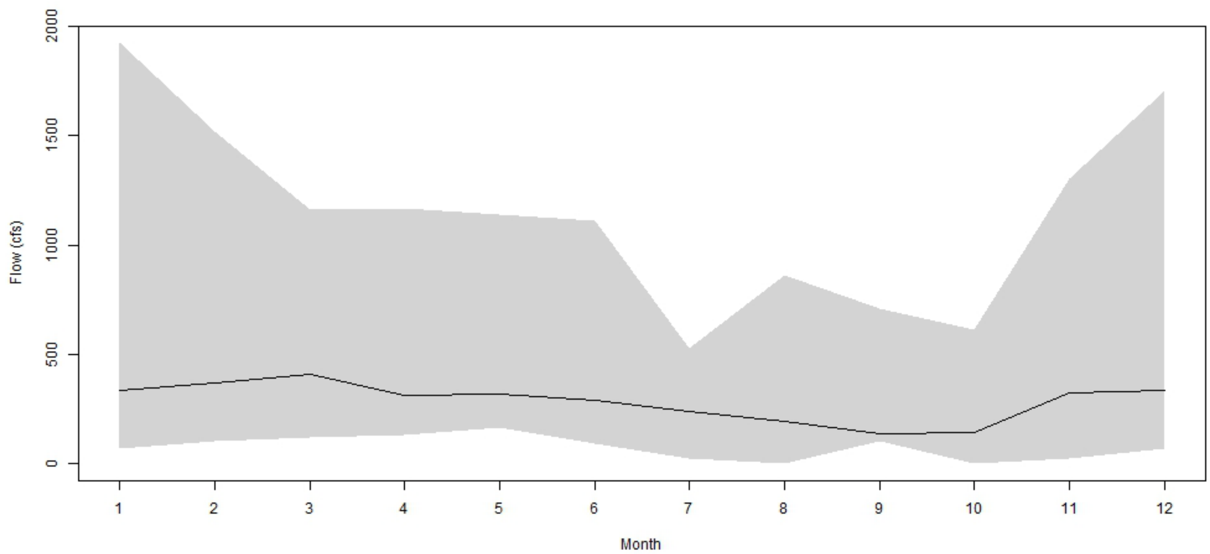


Figure 13. Comparison between monthly median simulated historical flows (solid black line) and the range between the 10th and 90th percentiles of the USGS regional regression method (gray shading) for the East Fork Hood River.

The results discussed above embody the comparative analyses for all 42 flow points. The statistical ranges covering reasonable values and trends (Figure 12) generally supported the associated the simulated historical flows, whereas questionable statistical ranges (Figure 13) generally conflicted with the simulated historical flows. Thus, although none of the simulated historical flows were bias corrected based on the USGS estimates, the comparisons provided credence to simulated historical flows in several locations where gage records were not available.

Figure 14 displays the probability distributions of the simulated historical and observed streamflows for the Hood River at Tucker Bridge. The simulated historical values are consistently higher than those observed because the DHSVM model does not account for upstream diversions, reservoir operations, or any other anthropogenic modifications to the natural flow regimes. Also shown are the mean values of 895 cfs and 712 cfs for the simulated historical and observed flows, respectively, which are plotted against the appropriate percentiles that these values correspond to. Adding the annual average of diverted flows used to naturalize the observed record for calibration, 170 cfs (WPN 2013a), to the observed mean yields 882 cfs. These results indicate that modeled flows are within 1 percent of the naturalized observed flows at this location.

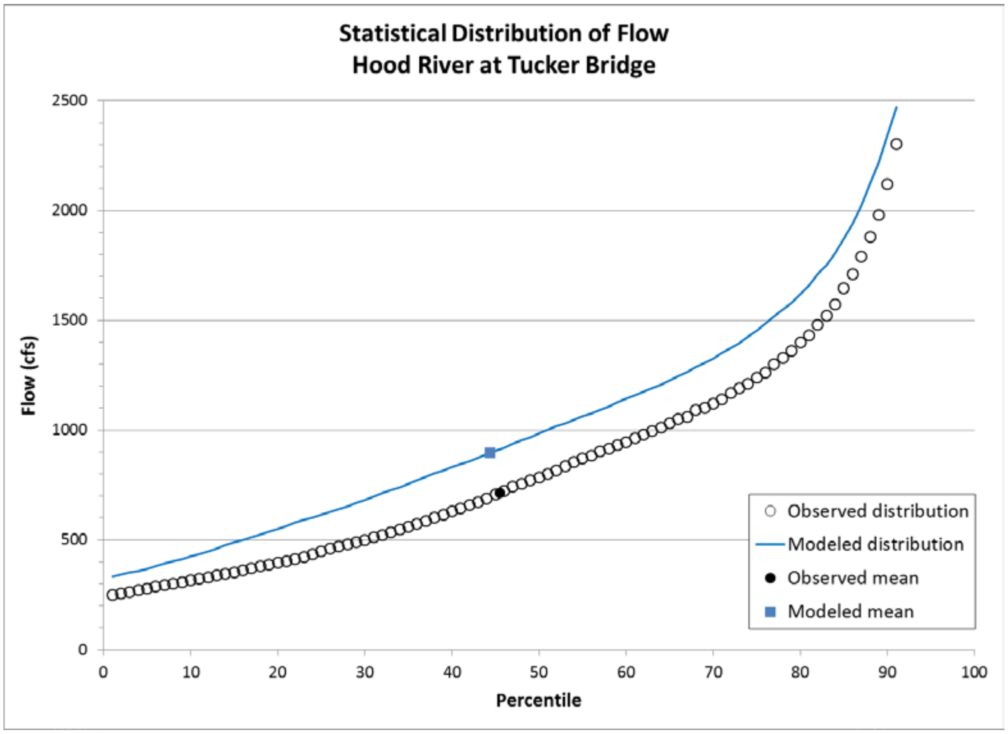


Figure 14. Statistical comparison of simulated historical and observed streamflows for the Hood River at Tucker Bridge.

Similarly, the results for the West Fork Hood River are shown in Figure 15. The modeled probabilistic distribution of flow for this location is very similar to the distribution of the observed record. This is a reasonable result given that relatively little water use occurs upstream. The annual average of monthly upstream diversions, including the Dee Canal and diversions off Green Point Creek, is approximately 14 cfs. The modeled and observed means are 383 cfs and 370 cfs, respectively. Adding the average diverted amount to the observed mean yields 384 cfs, indicating that modeled flows are also within 1 percent of the naturalized observed flows at this location.

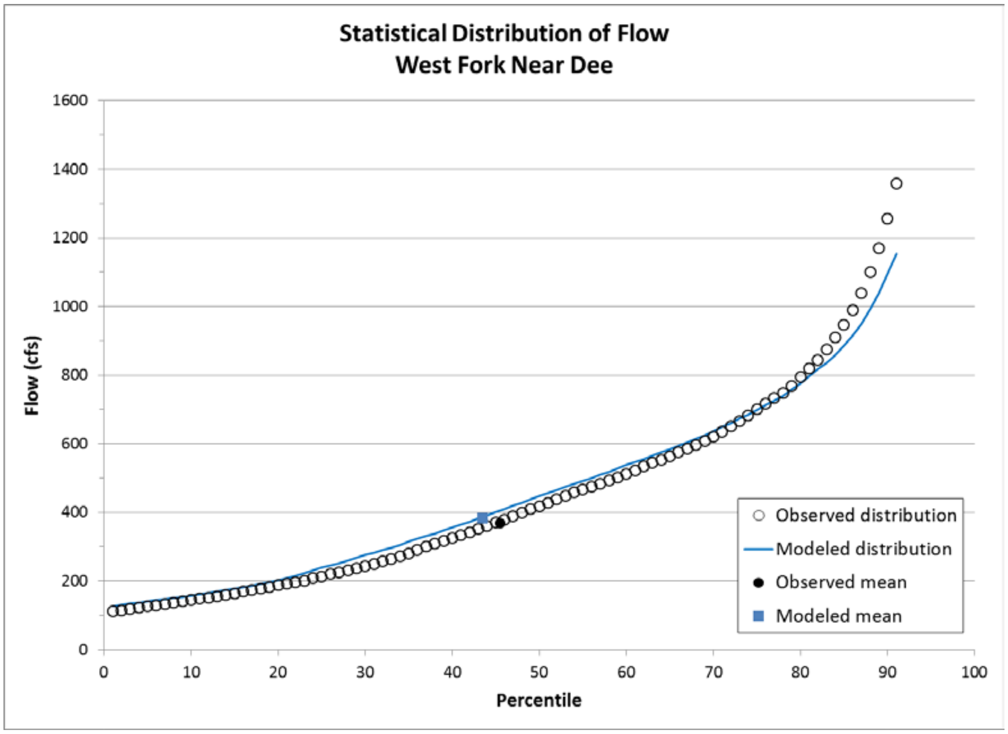


Figure 15. Statistical comparison of simulated historical and observed streamflows for the West Fork Hood River near Dee.

4.0 FUTURE CLIMATE CHANGE RESULTS

The DHSVM model was used to simulate potential future hydrologic patterns using climate change projections from the Climate Model Intercomparison Project (CMIP) Third Assessment Report. Please refer to the accompanying Climate Change Technical Memorandum for additional details on selecting climate change scenarios and generating the adjusted meteorological forcings for input to the DHSVM model.

Figure 16 illustrates a summary of the climate change scenarios selected for this Basin Study. Three scenarios were chosen for hydrologic modeling to represent more warming and dry (MW/D) conditions, less warming and wet (LW/W) conditions, and median (MED) conditions. This naming convention recognizes that adjustments in precipitation are both greater than and lower than historical precipitation and that adjustments in temperature are all greater than historical temperature. The MED scenario simply represents the statistical center of the adjustments. The MW/D, LW/W, and MED scenarios were selected over other potential scenarios based on the ability to provide the largest range of future hydrologic conditions.

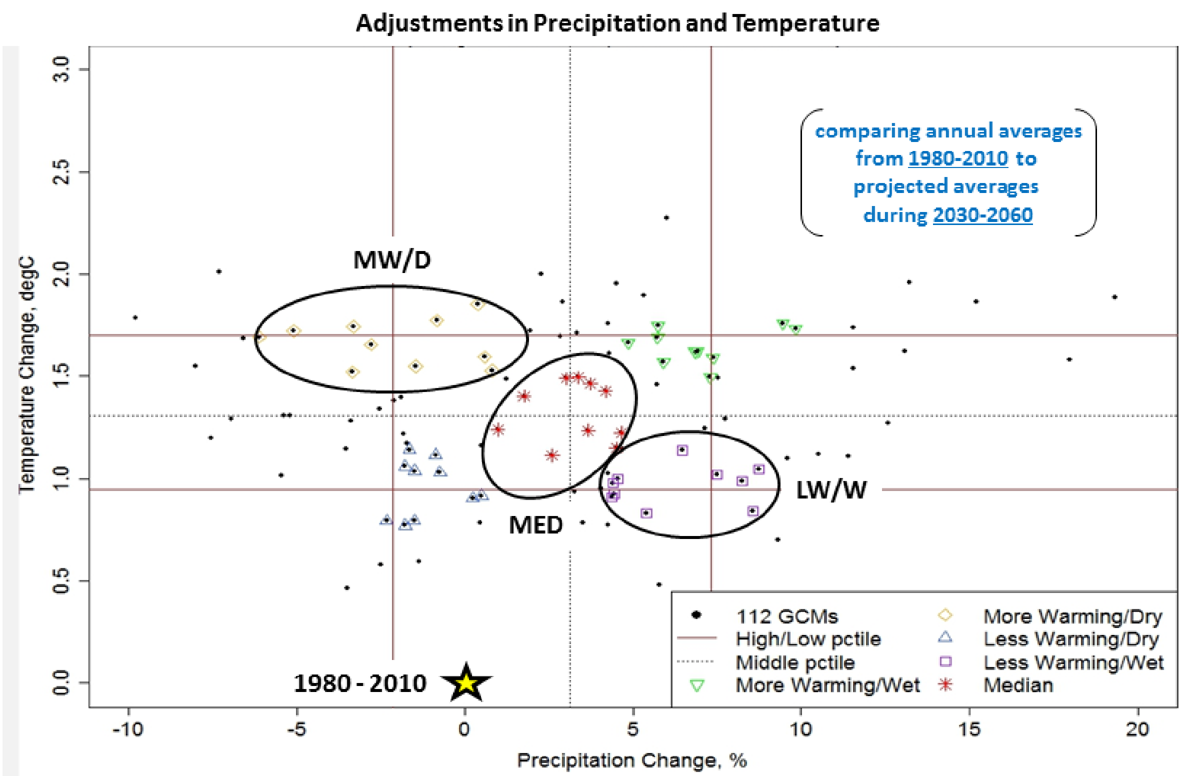


Figure 16. Summary of climate change projection selection results for the Basin Study.

4.1 Glacier Characteristics

The simulated impacts of the climate change scenarios on glacier volume and areal extent are displayed in Figure 17 and Figure 18. The future climate change meteorological forcings for the years 2030 through 2059 were used as input to the DHSVM model. However, because forcings data for the water years 2010 through 2029 period were not available and the glacier extension of the DHSVM model must run continuously, the state of the glaciers in October 2009 (Figure 8) was used as the initial state to simulate the water years 2030 through 2059 time period. Because of this, there is a gap in glacier response to a changing climate between 2010 and 2029. Thus, the results are qualitative until forcings for the water years 2010 through 2029 period can be used to update the DHSVM model so it can be run continuously through 2059.

To enable comparisons to the full historical period provided in Section 3.1, the glacier volume and extent values in Figure 17 and Figure 18 are again relative to the beginning of the 1920 water year. For clarity, the results are plotted against a generic 30-year period. However, the BASE simulation represents the water years 1980 through 2009 portion of the simulated historical period and the climate scenario simulations represent the water years 2030 through 2059 period.

Whereas the BASE simulation indicates glacier volume has remained effectively unchanged over nearly the last 100 years (Section 3.1), applying the climate scenario adjustments to temperature and precipitation yields approximately 4 to 12 percent losses in volume over the future 30 year simulation period. The losses in areal extent are less dramatic at approximately 1 to 4 percent, which is contrary to the simulated historical results (Section 3.1). This might suggest that glacier recession is modeled to quickly creep into the existing larger ice masses of the accumulation zone. However, because the modeled glaciers were not evolved through a changing climate between water years 2010 and 2029, but were abruptly faced with the projected climate conditions of water years 2030 through 2059, the simulated changes in glacier volume and extent should be viewed in a qualitative manner. The ice masses will likely be very different in 2030 from the modeled states at the end of 2009 (Chris Frans, personal communication, March 19, 2014).

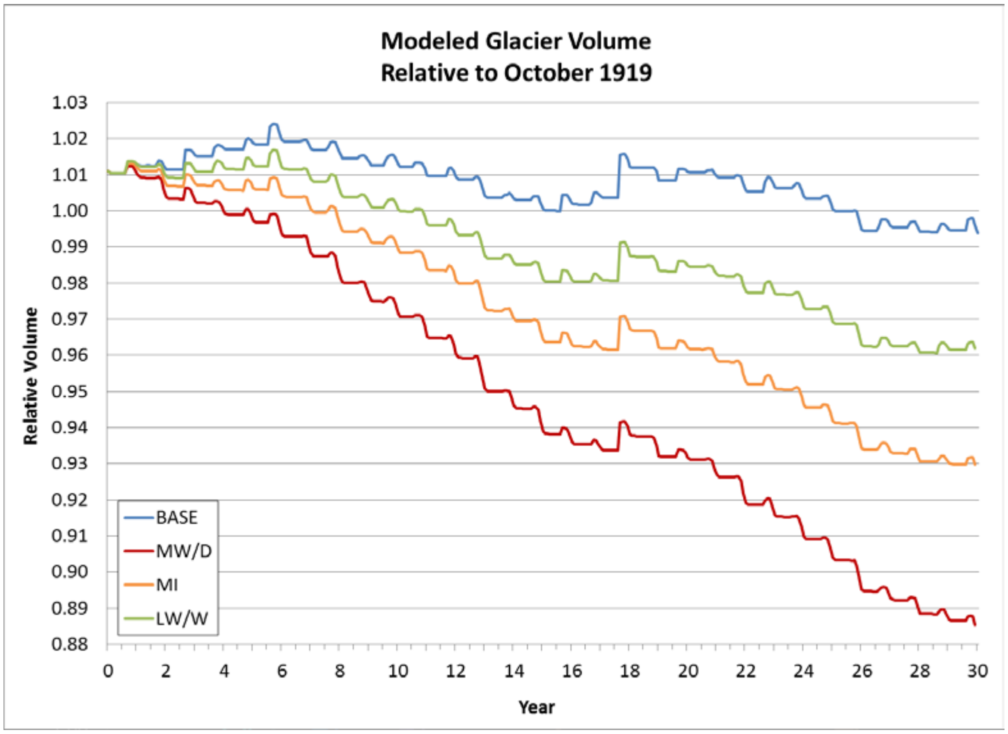


Figure 17. Comparison of simulated historical glacier volume with simulated future glacier volume under each climate scenario.

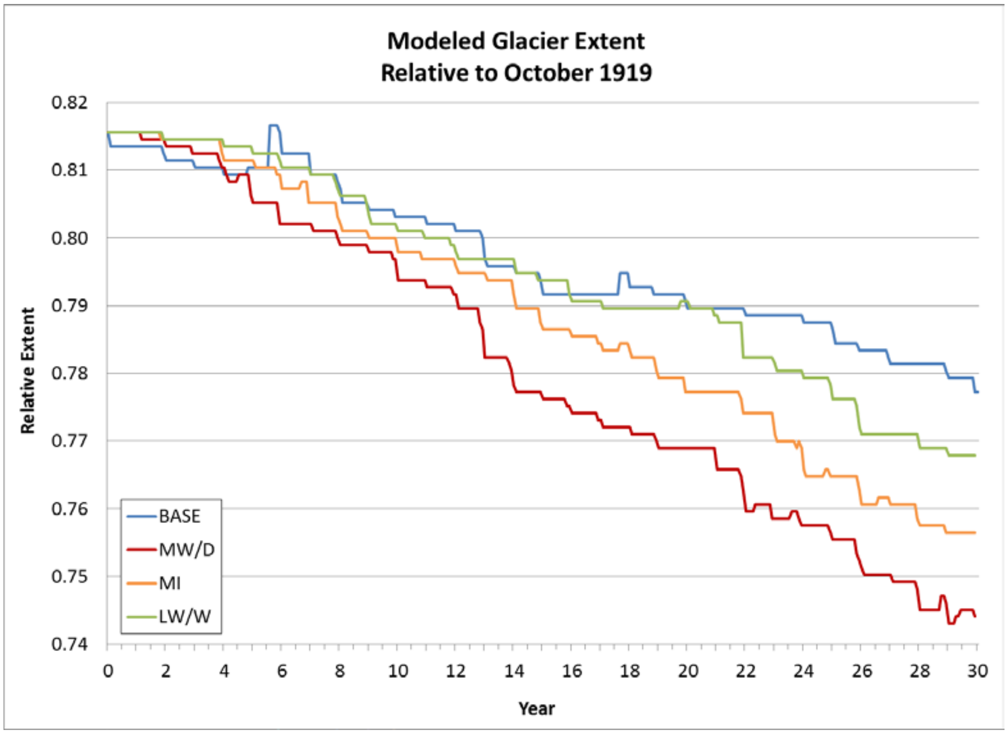


Figure 18. Comparison of simulated historical glacier extent with simulated future glacier extent under each climate scenario.

Because of the abrupt application of the future climate conditions, the warmer temperatures of the climate scenarios act to increase flows from glacial melt water, primarily during the warmest months of July and August. Figure 19 through Figure 21 illustrate the modeled glacial melt contributions to streamflow along the Eliot Branch, Middle Fork Hood River, and mainstem Hood River, respectively. Although each location is modeled to have additional glacier-fed flow under the climate scenarios, quantitative confidence in these results should be tempered because of the caveat discussed above.

Considering the spread in DHSVM model results (indicated by the "error" bars, representing the 10th and 90th percentiles of model results), glacial melt may currently contribute nearly 70 percent of the total flow in Eliot Branch during the summer. Downstream along the Middle Fork Hood River, which includes flows from Eliot Branch, glacier-fed Coe Creek, and Clear Branch, nearly a quarter of summer flows may be attributable to the glaciers sitting atop its headwaters. Along the mainstem Hood River, these contributions amount to less than 10 percent. However, as shown in Figure 22, this proportion represents approximately 20 cfs during the critical late summer period. Under the climate scenarios, this is modeled to increase by approximately 5 to 15 cfs. As will be discussed below, however, the modeled decreases in snowpack and snow melt contributions to streamflows effectively negate any modeled future increases in flows from glacial melt.

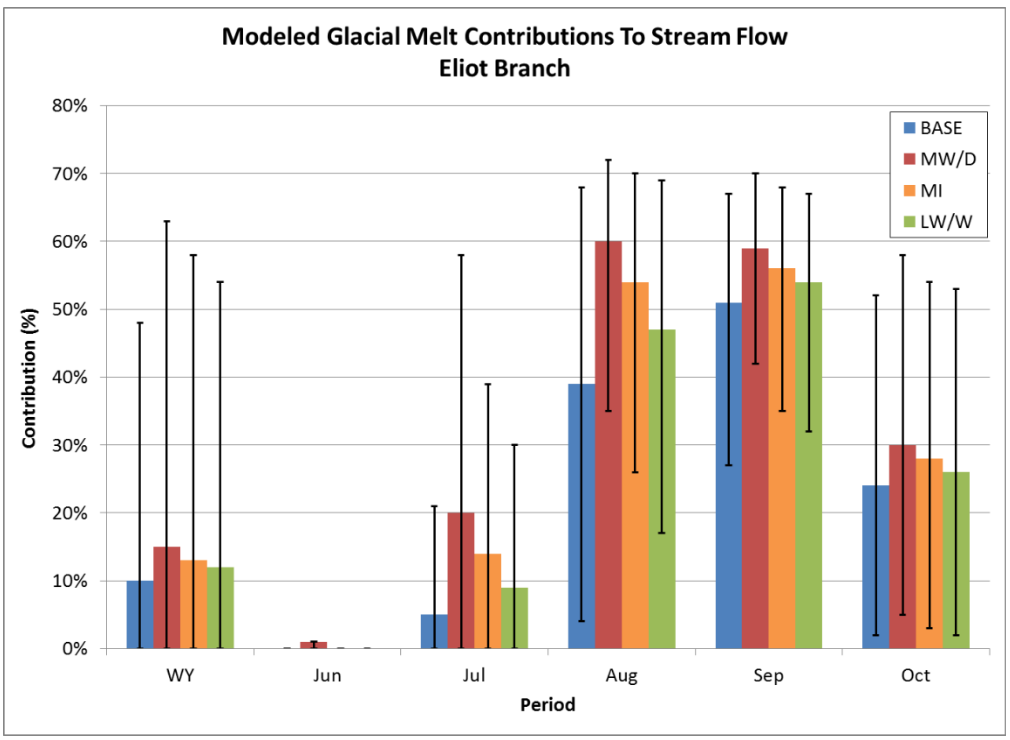


Figure 19. Comparison of simulated historical glacier melt contributions with simulated future glacier melt contributions under each climate scenario for Eliot Branch.

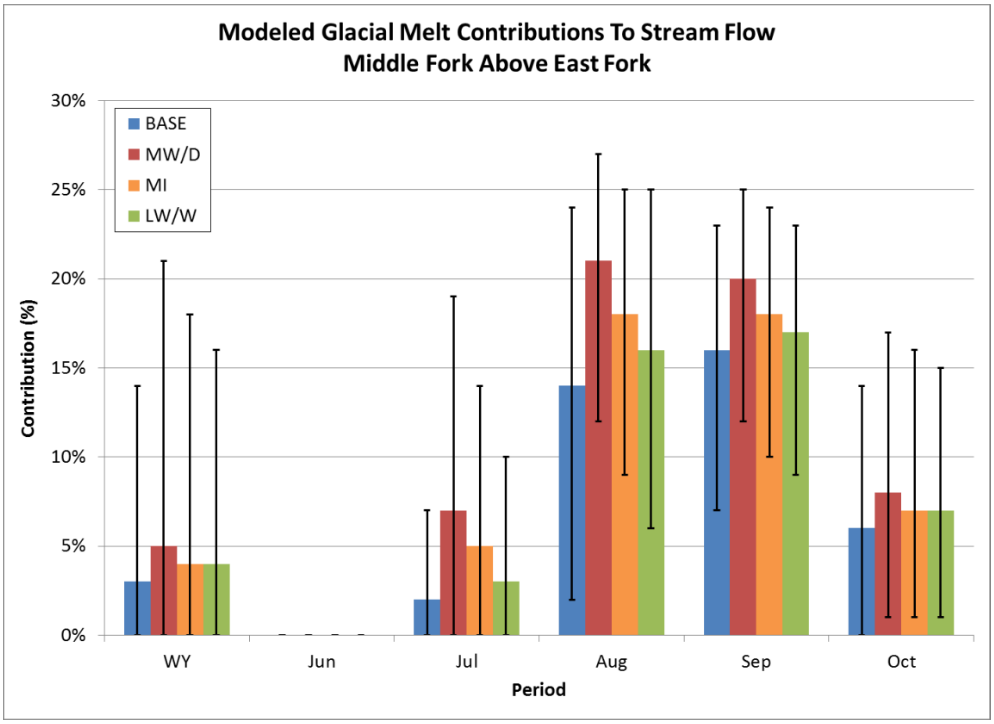


Figure 20. Comparison of simulated historical glacier melt contributions with simulated future glacier melt contributions under each climate scenario for the Middle Fork Hood River.

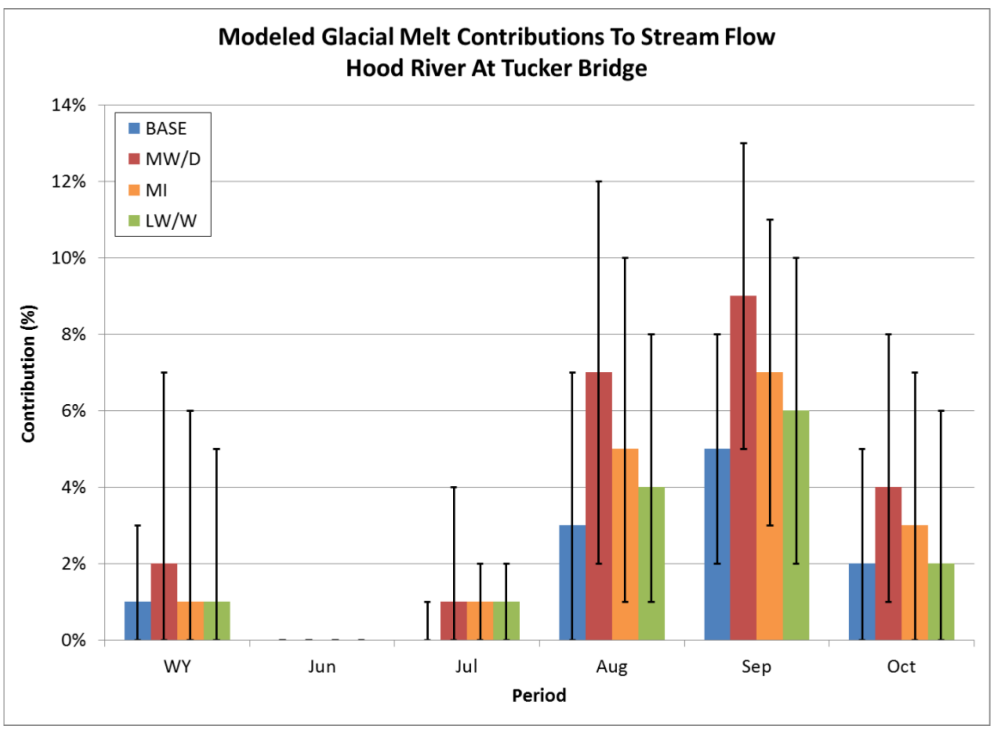


Figure 21. Comparison of simulated historical glacier melt contributions with simulated future glacier melt contributions under each climate scenario for the mainstem Hood River at Tucker Bridge.

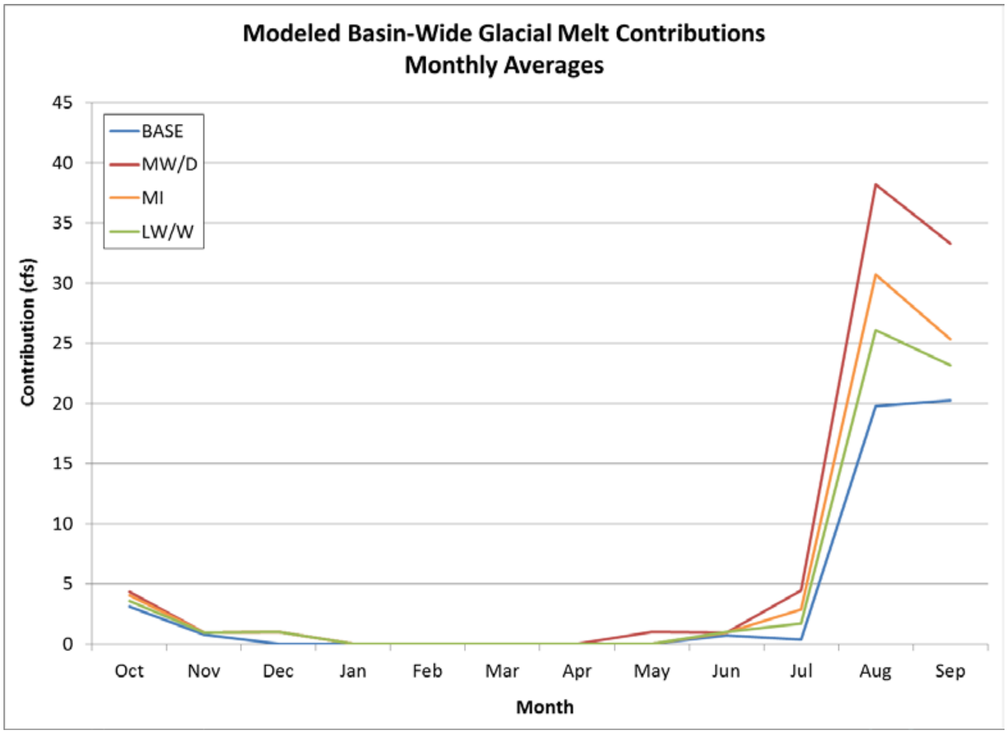


Figure 22. Comparison of simulated historical glacier melt contributions (in cfs) with simulated future glacier melt contributions (in cfs) under each climate scenario for the entire Basin.

4.2 Snowpack

A summary of the snow extent results for the simulated historical and simulated future DHSVM model runs is provided in Figure 23. With the projected warmer temperatures, all three climate scenario simulations yield less snowpack than the simulated historical run. The primary implication of these results is less snow melt-driven streamflow during the spring and summer months. Figure 24 illustrates the average modeled contributions of snow melt to streamflows for the entire Basin. The largest decreases (approaching 200 cfs) occur in May. Although much smaller, the decreases in August (up to 15 cfs) are on the scale of the projected increases in glacial melt discussed above; thus, the net impact of these two processes is negligible for impacting streamflows during the late summer. However, the larger decreases in snow melt contributions in April through July imply that natural streamflows may be significantly impacted during the spring and early summer periods.

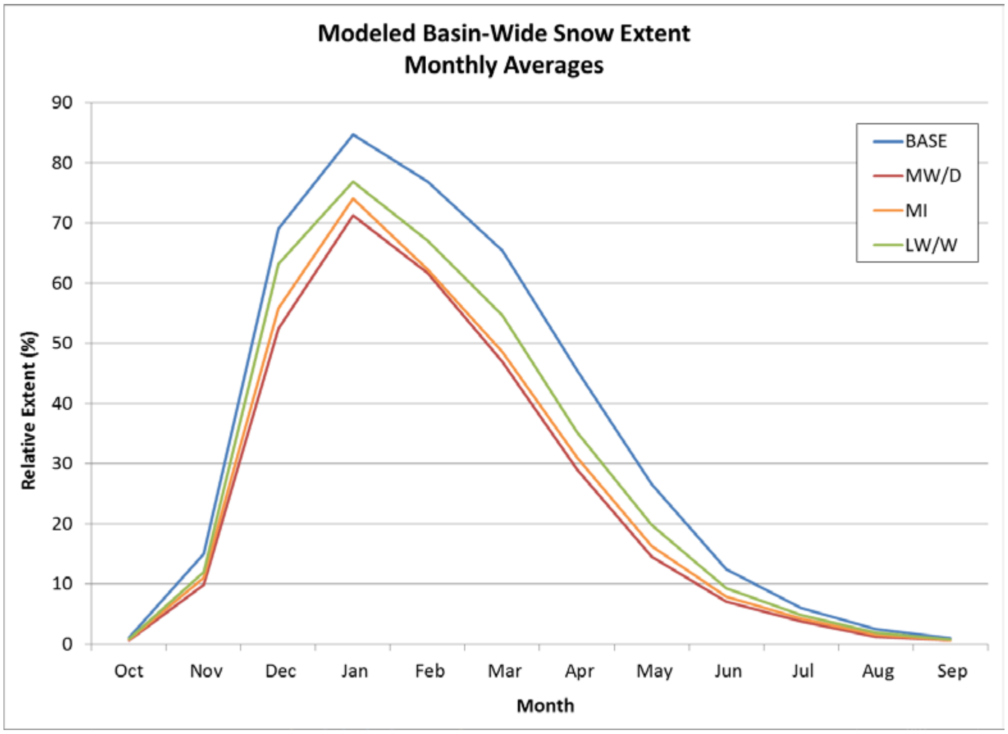


Figure 23. Comparison of simulated historical snow extents with simulated future snow extents under each climate scenario for the entire Basin.

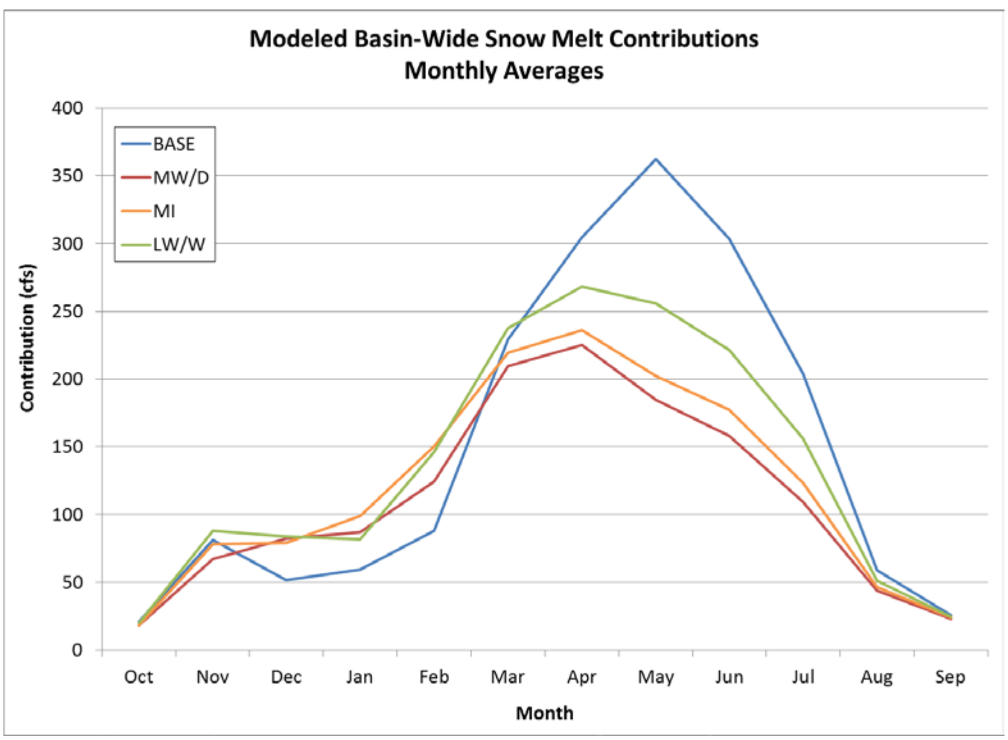
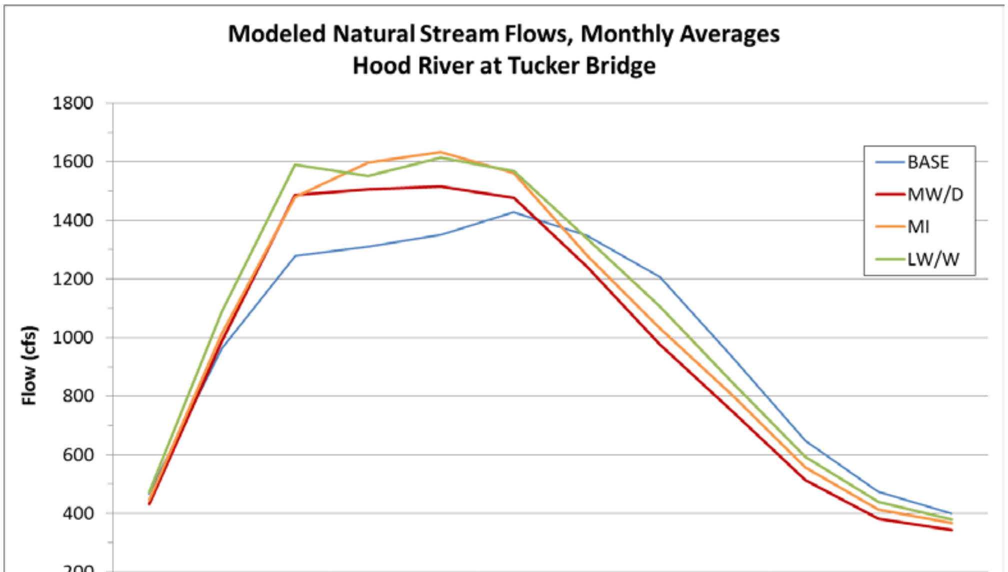


Figure 24. Comparison of simulated historical snow melt contributions (in cfs) with simulated future snow melt contributions (in cfs) under each climate scenario for the entire Basin.

4.3 Streamflow

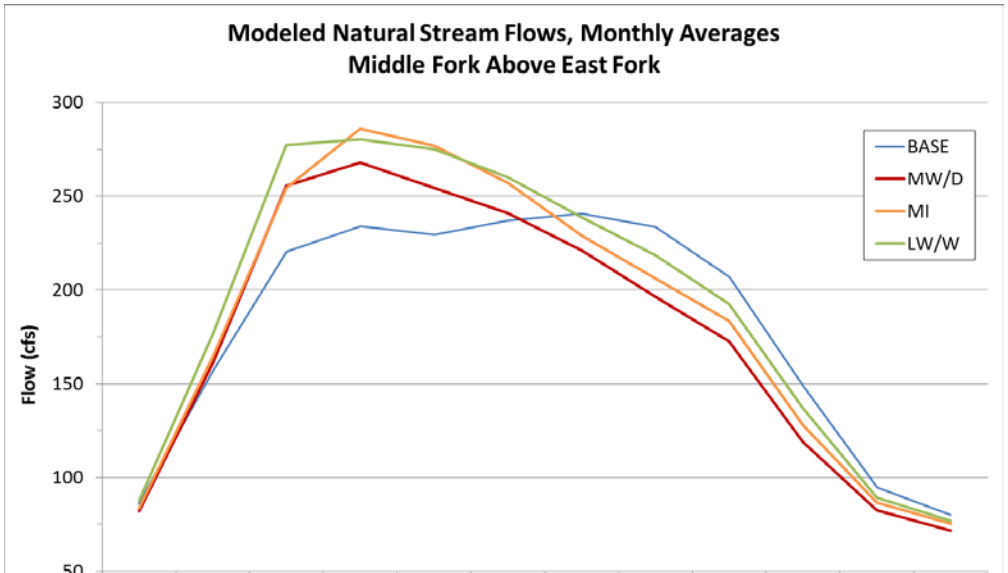
The projected decreases in precipitation and increases in temperature during the spring and summer months (see accompanying Climate Change Technical Memorandum) are expected to yield overall lower streamflows during the irrigation season. Figure 25 provides the simulated monthly average natural flows of the Hood River at Tucker Bridge in graphical and tabular form. The annual hydrographs of the climate scenario simulations illustrate that the shape of annual runoff is compressed and skewed compared to the simulated historical hydrograph. Peak flows are higher but flows on the receding limb of the hydrograph and base flows are lower. Although on an annual basis the changes in runoff are less than 5 percent (i.e., comparing the annual mean flows of the climate scenario simulations to the BASE simulation), the monthly averages indicate up to 20 percent less flow during the critical water use period between May and September.

Figure 26 through Figure 28 provide individual results for each of the three main forks of the Hood River. The above summary of results for the mainstem Hood River generally applies to the results below, with the exception that the modeled future decreases in flows through the East Fork Hood River approach 30 percent during the summer months (Figure 27).



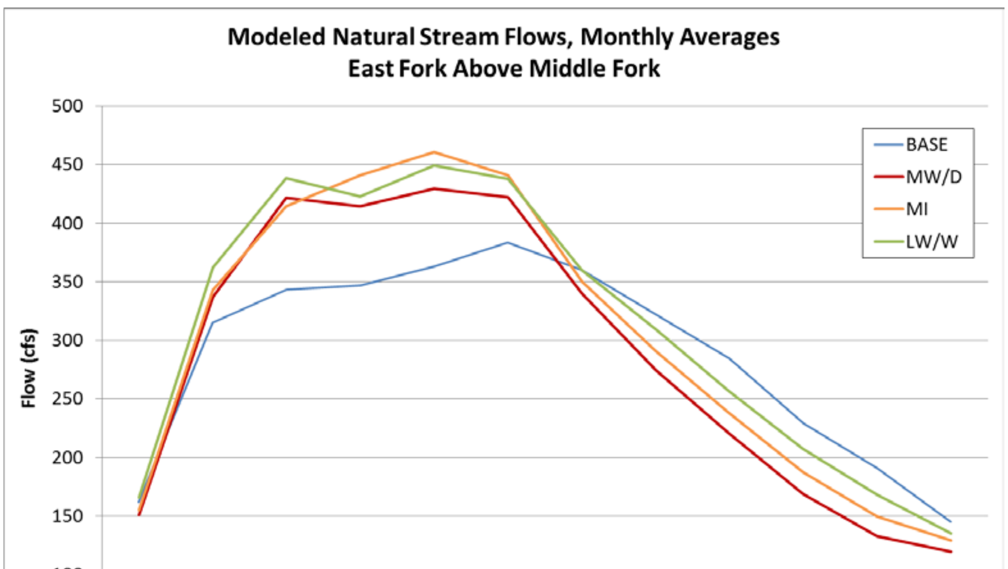
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
BASE	467	964	1278	1311	1351	1429	1348	1206	932	647	475	398
MW/D	432	987	1485	1506	1517	1476	1241	977	747	515	383	343
MI	448	1013	1478	1598	1633	1560	1280	1032	802	557	412	368
LW/W	474	1087	1590	1552	1613	1567	1337	1107	846	594	438	379

Figure 25. Comparison of simulated historical streamflow (in cfs) with simulated future streamflow (in cfs) under each climate scenario for the Hood River at Tucker Bridge.



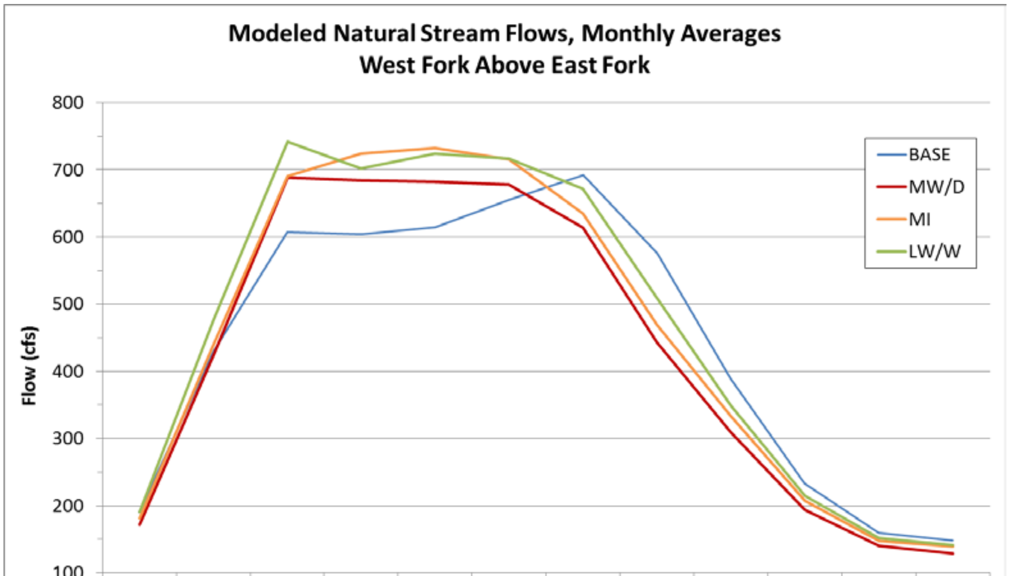
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
BASE	86	157	221	234	229	237	241	233	207	149	95	80
MW/D	82	161	255	268	255	241	221	196	172	119	83	71
MI	84	165	254	286	277	257	229	206	183	128	86	75
LW/W	88	177	277	280	275	260	239	218	192	137	89	77

Figure 26. Comparison of simulated historical streamflow (in cfs) with simulated future streamflow (in cfs) under each climate scenario for the Middle Fork Hood River.



	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
BASE	162	315	343	347	363	383	360	322	284	229	191	145
MW/D	151	337	422	415	430	422	340	274	220	169	133	119
MI	155	343	414	441	461	441	350	290	238	187	150	129
LW/W	166	362	439	423	449	438	360	309	256	207	168	135

Figure 27. Comparison of simulated historical streamflow (in cfs) with simulated future streamflow (in cfs) under each climate scenario for the East Fork Hood River.



	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
BASE	190	429	607	604	615	656	692	576	390	234	160	148
MW/D	172	425	689	684	682	678	614	444	309	194	141	129
MI	181	440	690	724	733	716	635	470	333	208	148	139
LW/W	191	477	742	702	724	717	672	509	348	215	151	141

Figure 28. Comparison of simulated historical streamflow (in cfs) with simulated future streamflow (in cfs) under each climate scenario for the West Fork Hood River.

5.0 CONCLUSIONS

The DHSVM model was calibrated to historical observations of glacier characteristics, snow water equivalent (SWE), and streamflows. The full simulated historical period encompasses water years 1916 through 2009 (October 1915 through September 2009). However, because the glacier extension required a few simulation years to stabilize, DHSVM output for water years 1916 through 1919 were generally excluded from analyses.

The simulated historical glacier volumes and extents follow the observed trends reported in scientific literature, which indicate that the Basin's glaciers have been steadily receding since at least the mid-1900s. Simulated historical SWE captures the seasonal trends and year-to-year variability of observed SWE from three SNOTEL stations in and near the Basin. The observed seasonal peak SWE is under-represented by the DHSVM model. However, future efforts should include removing tree cover from the DHSVM model grid cells representing these station locations, and re-running the model to evaluate if the lack of tree cover at the physical station locations is the primary reason for the apparent discrepancies between simulated and observed SWE. Lastly, simulated historical streamflows are quality analogs of naturalized observed streamflows along the West Fork Hood River and mainstem Hood River, suggesting that the DHSVM model is well-suited to estimate the timing and quantity of natural surface runoff in the Basin.

To simulate the impacts of projected future climate change on natural streamflows, the DHSVM model was also run using adjusted meteorological forcings developed to represent various climate scenarios for water years 2030 through 2059. Because glacial and meteorological data representing the transition period of water years 2010 through 2029 were not available, October 2009 was selected as the initial state of the DHSVM model for the simulated future runs. Therefore, results regarding projected changes in glacier volumes, extents, and melt contributions to streamflows should be viewed in a qualitative manner. Future efforts should investigate evolving the glaciers through the transition period of water years 2010 through 2029 prior to applying the climate scenario forcings.

Comparisons of DHSVM model results for the 30 year periods representing the water years 1980 through 2009 historical (BASE) conditions and 2030 through 2059 future (climate scenario) conditions suggest that the seasonal timing and quantities of natural streamflows in the Basin will be altered by climate change. The DHSVM model indicates that the glaciers continue receding and snowpack decreases, namely during the spring and summer months, under the projected warmer future temperatures. Although the projected changes in precipitation and temperature are simulated to increase streamflows during the fall and winter months, the overarching impact of climate change on the hydrology of the Basin is expected to be decreased streamflows during the water use-critical spring and summer seasons.

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