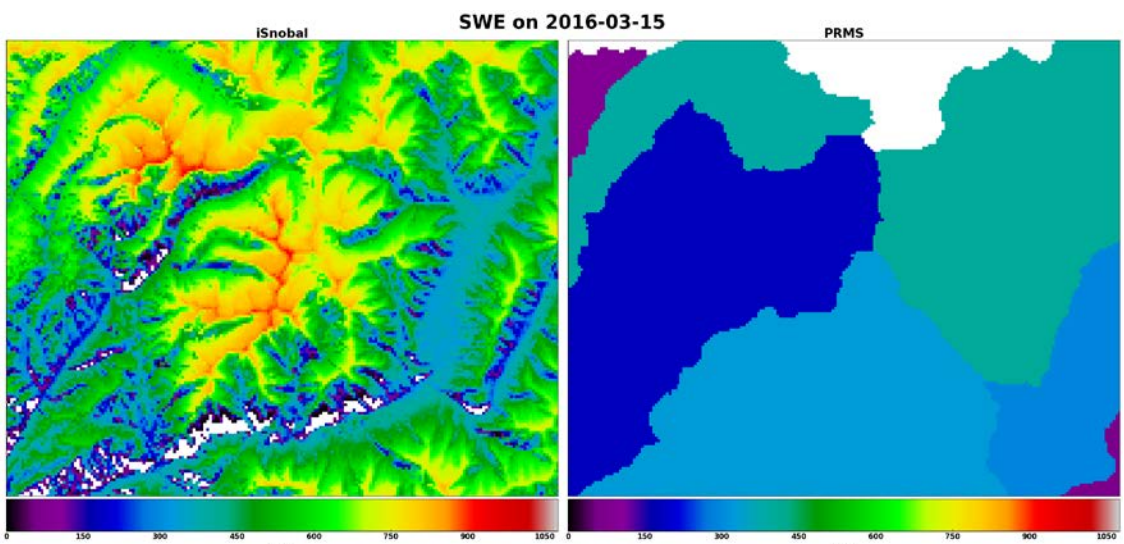
RECLAMATION
Managing Water in the West

Enhancing Prediction of Climate Change Impacts on Snow Distribution and Melt Patterns in the Mountain West

Research and Development Office
Science and Technology Program
(Final Report) ST-2016-8106-1



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

January 2017

U.S. DEPARTMENT OF THE INTERIOR

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

MISSION OF THE BUREAU OF RECLAMATION

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*
T1. REPORT DATE 12/2016	**T2. REPORT TYPE Research**	**T3. DATES COVERED**
T4. TITLE AND SUBTITLE Enhancing Prediction of Climate Change Impacts on Snow Distribution and Melt Patterns in the Mountain West		**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER** 1541 (S&T)
6. AUTHOR(S) Scott Havens, 208-426-0729 scott.havens@ars.usda.gov Daniel Marks, 208-426-0721 danny.marks@ars.usda.gov Eric Rothwell, 208-378-5370 erothwell@usbr.gov		**5d. PROJECT NUMBER** 8106 **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Daniel Marks USDA-ARS Scott Havens USDA-ARS Eric Rothwell Bureau of Reclamation, Pacific Northwest Region		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research and Development Office U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007		**10. SPONSOR/MONITOR'S ACRONYM(S)** **R&D: Research and Development Office** **BOR/USBR: Bureau of Reclamation** **DOI: Department of the Interior** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** ST-2015-2264-1

12. DISTRIBUTION / AVAILABILITY STATEMENT
Final report can be downloaded from Reclamation's website: https://www.usbr.gov/research/

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 words)*
Results from models run at different scales, from the regional down to the hill slope scale, are dependent on the process parameterizations and calibrations of the physics being represented. This project compared the application of two models that could be used for climate change predictions of snowmelt, a physically based gridded snowmelt model and a coarse lumped parameter model, over the Boise River Basin. The results showed that, while the calibrated parameter model could estimate the streamflow volumes at a yearly and monthly time scale, the volume of water stored in the snowpack was underestimated. Whereas the physically based snow model could accurately estimate the snowpack accumulation and ablation when compared to the in-situ measurement sites. When addressing climate change impacts on the prediction of snow distribution and melt patterns, USDA ARS recommends to use physically based models that have limited calibration and represent the underlying physical processes of the hydrologic system. While lumped parameter models can be quickly developed, robust calibration must be performed to ensure that the resulting parameters represent the physical processes of the system. If the parameters are not representative, then the climate change predictions will have a high level of uncertainty.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: **Unclassified**			**17. LIMITATION OF ABSTRACT** **U**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U			**19b. TELEPHONE NUMBER** **303-445-2125**

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

PEER REVIEW DOCUMENTATION

Project and Document Information

Project Name: Enhancing Prediction of Climate Change Impacts on Snow Distribution and Melt Patterns in the Mountain West

WOID: ____

Document Author(s): Daniel Marks, Scott Havens, Eric Rothwell

Document date: January 2017

Peer Reviewer Mary Mellema

Review Certification

Peer Reviewer: I have reviewed the assigned items/sections(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewer ______________________ (Signature) Date reviewed 1/23/17

Acronyms and Abbreviations

DEM	digital elevation model
DHSVM	Distributed Hydrology Soil Vegetation Model
DWR	Department of Water Resources
HRU	hydrologic response units
IQR	inter quantile range
km^2	square-kilometers
m	meter
mm	millimeters
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Efficiency
PRMS	Precipitation-Runoff Modeling System
Reclamation	U.S. Bureau of Reclamation
S&T	Science and Technology
SMRF	Spatial Modeling for Resources Framework
SWE	Snow water equivalent
SWI	Snow water input
USDA ARS	U.S. Department of Agriculture, Agricultural Research Service

EXECUTIVE SUMMARY

Results from models run at different scales, from the regional down to the hill slope scale, are dependent on the process parameterizations and calibrations of the physics being represented. This project compared the application of two models that could be used for climate change predictions of snowmelt, a physically-based gridded snowmelt model and a coarse lumped parameter model, over the Boise River basin. The results showed that, while the calibrated parameter model could estimate the streamflow volumes at a yearly and monthly time scale, the volume of water stored in the snowpack was underestimated. Whereas, the physically-based snow model could accurately estimate the snowpack accumulation and ablation when compared to the in-situ measurement sites. When addressing climate change impacts on the prediction of snow distribution and melt patterns, the U.S. Department of Agriculture, Agricultural Research Service (USDA ARS) recommends using physically-based models that have limited calibration and represent the underlying physical processes of the hydrologic system. While lumped parameter models can be quickly developed, robust calibration must be performed to ensure that the resulting parameters represent the physical processes of the system. If the parameters are not representative, then the climate change predictions will have a high level of uncertainty.

Contents

Contents (continued)

List of Figures

PROJECT SUMMARY

The project aimed to answer two research questions:

1. How do differences in scale between models affect the underlying physical processes?

2. What is the future implication of climate change on streamflow?

Snow hydrologists have been working towards the coupling of a physically-based snowmelt model, *iSnobal*, with a subsurface hydrology model to estimate streamflow. We were not able to perform a full coupling as the first model chosen was a complicated physically-based hydrology model that was extremely difficult to calibrate in the Boise River basin due to the lack of data to parameterize the model. Therefore, a simpler hydrology model was chosen for easier parameterization that uses hydrologic response units (HRU) to represent the hydrologic system, though the coupling has not yet been performed. However, this is an area of extreme interest for ARS and will be addressed in a future project with the U.S. Bureau of Reclamation (Reclamation) in Sacramento (TBD).

STUDY AREA

The Boise River basin, defined in this study as the watershed above Lucky Peak Dam, is located just to the east of Boise, Idaho and encompasses roughly 7,000 square-kilometers (km^2) (Figure 1). The majority of the Boise River basin is within the rain-snow transition zone with elevation ranging from 858 meters (m) near the outlet to 3,187 m at its highest point. The basin has a multitude of land covers, comprised of forest (43%), shrub land (35%), herbaceous (21%), and other land covers (1%) based on analysis of the National Land Cover Database (Homer et al. 2015). The majority of winter precipitation occurs as snow, with average annual precipitation of 500 millimeters (mm) at lower elevations and 1,500 mm at higher elevations. The Boise River basin was divided up into 87 HRUs based on the subbasins and tributaries to the three major forks of the Boise River.

Within the Boise River basin, the U.S. Bureau of Reclamation (Reclamation) operates the Anderson, Arrowrock, and Lucky Peak reservoirs (U.S. Army Corps of Engineers' project) as a system to manage reservoir levels for flood control and water supply while also controlling flow levels to sustain fish populations and recreational uses. To provide irrigators water throughout the summer growing season, Reclamation water managers need accurate knowledge of the snowpack water volume and potential runoff generation in order to make the necessary management decisions. However, recently downscaled climate modeling in the Pacific Northwest has shown a shift to decreased snowpack accumulation, transition to rain, earlier runoff, and increased water demand associated with prolonged irrigation seasons (Brekke, Kuepper, and Vaddy 2010). In the Pacific Northwest, Reclamation has an extensive reservoir network ranging from snow dominated at higher elevations to rain dominated at lower elevations, but most are somewhere in between. Since most of the reservoirs are in that transitional zone, runoff can be from either rain, or snow with a high degree of variability from basin-to-basin and year-to-year.

There are 61 hourly meteorological stations in and around the basin used for *iSnobal* modeling, 14 Natural Resources Conservation Service (NRCS) SNOTEL stations used for the Precipitation-Runoff Modeling System (PRMS) modeling, 3 stream gauges, and the reservoir inflow at Lucky Peak Dam (Figure 1). The 14 NRCS SNOTEL stations provide precipitation, air temperature, and snow water equivalent with 3 sites measuring solar radiation and 5 sites measuring relative humidity. The other eight stations are from the Mesowest network (Horel et al. 2002) and are owned by Reclamation, Bureau of Land Management, the Sawtooth Avalanche Center, Idaho Transportation Department, and other small agencies. Mesowest instrumentation is site-dependent. These stations measure a combination precipitation, air temperature, relative humidity, solar radiation, and wind.

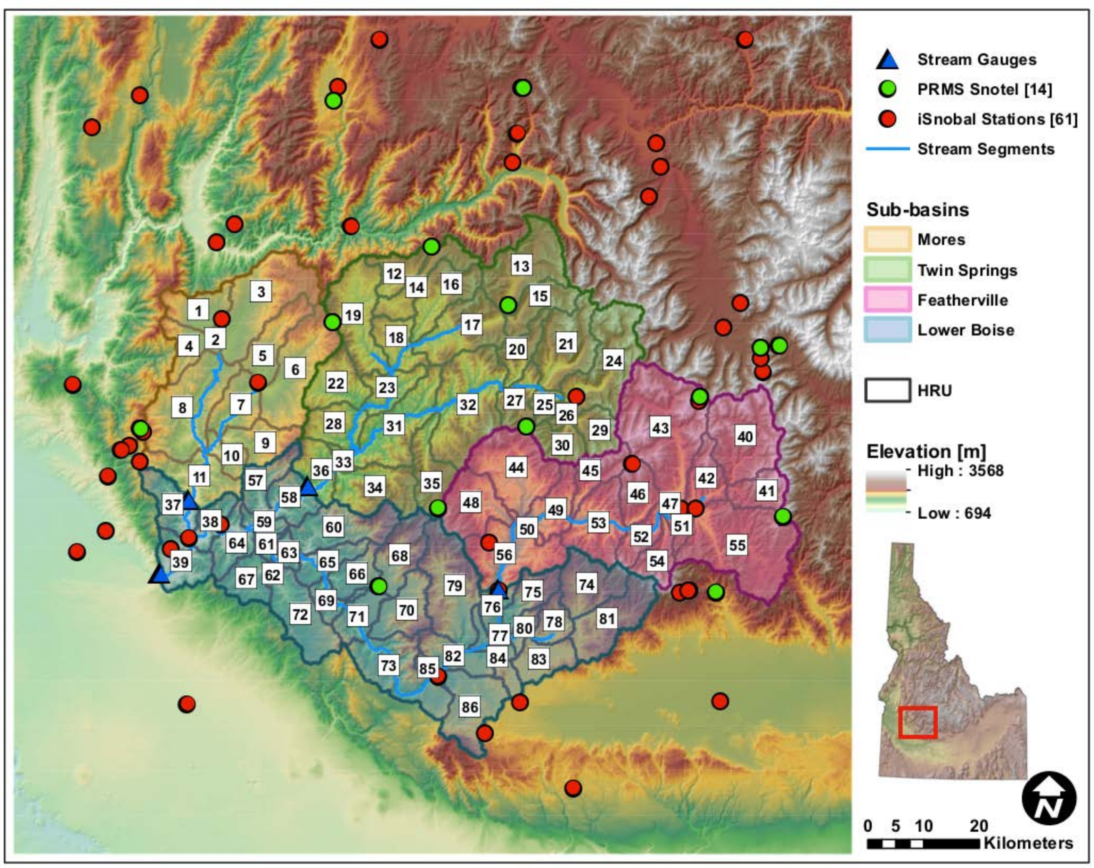


Figure 1. The Boise River basin with subbasins Mores Creek, Twin Springs, and Featherville (from left to right). The subbasins are further divided into HRUs to represent the hydrologic modeling components. NRCS SNOTEL stations, Mesowest stations, stream gauges, and reservoir inflows are shown.

Model Descriptions

The project investigated three different models that have a range of model complexity and physics representing the underlying snow and hydrologic processes. Major differences between the models are the methods for dividing the modeling domain. The two physically-based models are grid based with the lumped parameter model dividing the domain into HRUs. The differences in model discretization and scale must be accounted for when performing a model coupling or comparing two models.

iSnobal

The physically-based, distributed snowmelt model, *iSnobal* (Marks et al. 1999), is a grid-based energy and mass balance model run over a digital elevation model (DEM). *iSnobal* simulates the snowpack as two layers, with the active surface layer exchanging energy with the atmosphere and the lower layer transferring energy between the snow surface layer and soil. The snow temperature, density, and liquid water content are calculated for each layer. *iSnobal* forcing data inputs are raster surfaces of incoming thermal (long-wave) radiation, air temperature, vapor pressure, wind speed, soil temperature, and net solar radiation in addition to the precipitation mass, temperature, phase, and percent snow. Given the forcing data, the energy balance, snow temperature, depth, mass, and cold content are computed for each grid cell. Melt cannot occur until the temperature of the snow cover is at zero degrees Celsius, at which point the cold content equals zero. Liquid water drainage from the snow does not occur until the liquid water holding capacity of the snow is exceeded.

Numerous research studies have applied *iSnobal* in various mountain settings across the United States, Canada, and Europe. These studies have recreated the snowpack for past years using carefully crafted meteorological data and compare favorably with snow surveys, pillows, and other measurements. An early test demonstrating the potential of *iSnobal* for operational river basin applications was conducted retroactively for a single month during melt (April, 1990) (Garen and Marks 1996) and then for three snow seasons (1998 to 2000) in the Twin Springs subbasin (2,150 km^2) of the Boise River (Garen and Marks 2005). The past 4 years (water years 2013 to 2016), USDA ARS ran *iSnobal* in near real time and distributed weekly model results to Reclamation and other interested agencies. The projects (Havens et al. 2015; Havens, Marks, and Rothwell 2016) showed that a physically-based, distributed snowmelt model could be run operationally over a large area and provide meaningful results to operational water managers to qualitatively aid in their decision-making process.

Distributed Hydrology Soil Vegetation Model

The Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta, Vail, and Lettenmaier 1994) provides a spatial representation of physical watershed processes over a DEM. DHSVM is a complete hydrologic model, accounting for atmosphere-surface mass and energy exchanges, like interception and evapotranspiration, over a gridded surface. DHSVM tracks water from precipitation inputs, through the vegetation canopy, and into the soil where water is routed vertically and laterally to the stream network.

In the Science and Technology (S&T) report 2264, the overland, subsurface, and stream routing schemes as well as the non-snow-covered surface evaporation scheme were decoupled from DHSVM and loosely coupled to *iSnobal*. The routing modules of DHSVM were used to take *iSnobal* surface water inputs and route the water to the stream network and simulate streamflows. The project was successful in simulating streamflows but required more calibration over a longer time period. Due to the complex nature of the physical processes of subsurface flow, evaporation, and water routing, many of the physical processes required significant parameterization. The parameterization of DHSVM is possible in research study basins were significant resources have surveyed the soil and vegetation in great detail, but estimating parameters in non-research basins prove to be difficult due to the limited soil and vegetation surveys required to estimate al the required inputs to DHSVM. This was a main reason that we have moved to a simpler hydrologic model where parameters can be estimated using publically-available resources and knowledge of soil and vegetation within a basin.

Precipitation-Runoff Modeling System

The PRMS (Leavesley et al. 1983; Markstrom et al. 2015) is a distributed-parameter, physical-process hydrologic model that uses HRUs to represent larger areas of similar hydrologic processes. PRMS models the full hydrologic processes with canopy interceptions, evaporation, transpiration, stream routing, subsurface flow, and groundwater flow. Conceptually, each PRMS module performs a mass balance to route water from precipitation through the various model components, before generating streamflow. The model inputs are simple compared to the physically-based models above, requiring at a minimum daily precipitation and minimum and maximum air temperature. If data is available, solar radiation and evaporation can also be used as inputs to PRMS.

The project has moved to using PRMS instead of DHSVM for two main reasons. First, as stated above, the parameterization of PRMS does not require significant soil and vegetation surveys, but can be initially estimated from publically available datasets before calibration. Secondly, the California Department of Water Resources (DWR) and the NRCS have invested significant resources into getting PRMS into their daily operations and water supply forecasts.

METHODS

iSnobal

iSnobal was ran for water years 2013 to 2016, the same years for the S&T 2264 real time runs. However, more meteorological sites were utilized than the past real time runs and different methods were used to distribute the point measurement data over the DEM. A total of 61 measurement sites in and around the Boise River basin were utilized over the 4-year period (Figure 1). From the point measurements, the required forcing data was generated using the Spatial Modeling for Resources Framework (SMRF) (Havens et al. InReview) which was developed by USDA ARS. SMRF allows for simple and efficient distributed forcing data development for all the required inputs for *iSnobal*.

The required forcing data for *iSnobal* are air temperature, vapor pressure, precipitation, longwave radiation, shortwave radiation, and wind speed. The distributed forcing data for each year was generated with SMRF before running *iSnobal* at a 100-meter spatial and hourly temporal resolution. The *iSnobal* results had to be aggregated up to the HRU scale for comparison with PRMS. Each HRU had an associated mask that allowed aggregation of the *iSnobal* gridded results to the HRU scale. Within the HRU mask, model statistics were calculated like the mean, standard deviation, quantiles, and maximum values for snow water equivalent (SWE), snow water input (SWI), and fractional snow cover area.

PRMS

PRMS requires, at a minimum, daily precipitation, minimum and maximum daily air temperature. The daily point measurement data was gathered from 14 SNOTEL stations (Figure 1) from water year 1990 to 2016 and was distributed to the 100-meter *iSnobal* DEM using SMRF. For each HRU, the median air temperature and the mean precipitation were calculated. This provided the input required for PRMS using the climate_hru module.

The initial parameters for the HRUs were derived from two main datasets. The soils parameters were estimated using the SSGURO Database, maintained by the Soil Survey staff at NRCS (NRCS 2106). The vegetation parameters were initially estimated using the Landfire dataset for vegetation type, height, and cover (LANDFIRE 2016).

Calibration of PRMS was performed for the three stream gauge locations and the calculated reservoir inflow at Lucky Peak for the entire period of record. The objective of the calibration was to correctly simulate yearly and monthly water volumes, as this is an important aspect for reservoir water management operations. The daily runoff is important for flood forecasting, but the large HRUs would not provide adequate spatial resolution for these physical processes. To fully capture potential rain-on-snow events, HRUs would need to be smaller with emphasis placed on capturing different elevation bands.

The calibration procedures took multiple steps, first calibrating the monthly solar, evaporation, and transpiration parameters (Hay et al. 2006) using the program LUCA (Hay and Umemoto 2006). The second step calibrated the yearly water volumes to ensure that the water balance was estimated correctly by changing the parameters that affect evapotranspiration and ground water losses. The last step calibrated parameters controlling the monthly water volume. All parameters (Table 1), except for step one, were manually calibrated with further automatic calibration performed at a later time.

Table 1. Calibration procedure. Step 1 calibrated to estimated monthly solar and potential evapotranspiration (PET) estimates. Step 2 and 3 were manually calibrated to year and monthly water volumes.

Step	Measurements	Parameters
1	Solar and PET	dday_slope, dday_intcpt, jh_coef
2	Yearly water volume	gwsink_coef, jh_coef_hru, soil_moist_max
3	Monthly water volume	gwflow_coef, soil2gw_max, ssr2gw_rate, sat_threshold, slowceof_lin, slowcoef_sq, tmax_cbh_adj, tmin_cbh_adj

RESULTS

PRMS Calibration

The calibration of PRMS to yearly water volume showed a good fit with R2 values between 0.941 and 0.962 and a Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe 1970) between 0.923 and 0.962 (Figure 2). The calibrated parameters showed that there were significant groundwater losses that needed to be accounted for in order to correctly estimate the water balance. This assumption of groundwater losses is in alignment with the known geology of the area where fractured, weathered bedrock, and deep thermal hot springs are prevalent.

The calibration to the monthly water volumes was an iterative process to ensure that the simulated baseflow, hydrograph regression, and early spring snowmelt peaks aligned with measured volumes. The timing of monthly snowmelt controlled the performance of the model with R2 values between 0.834 and 0.904 and NSE between 0.842 and 0.891. Mores Creek had the lowest values (Figure 2) potentially due to the lower elevation that places the basin in the rain-snow transition zone and the summer water rights allocations.

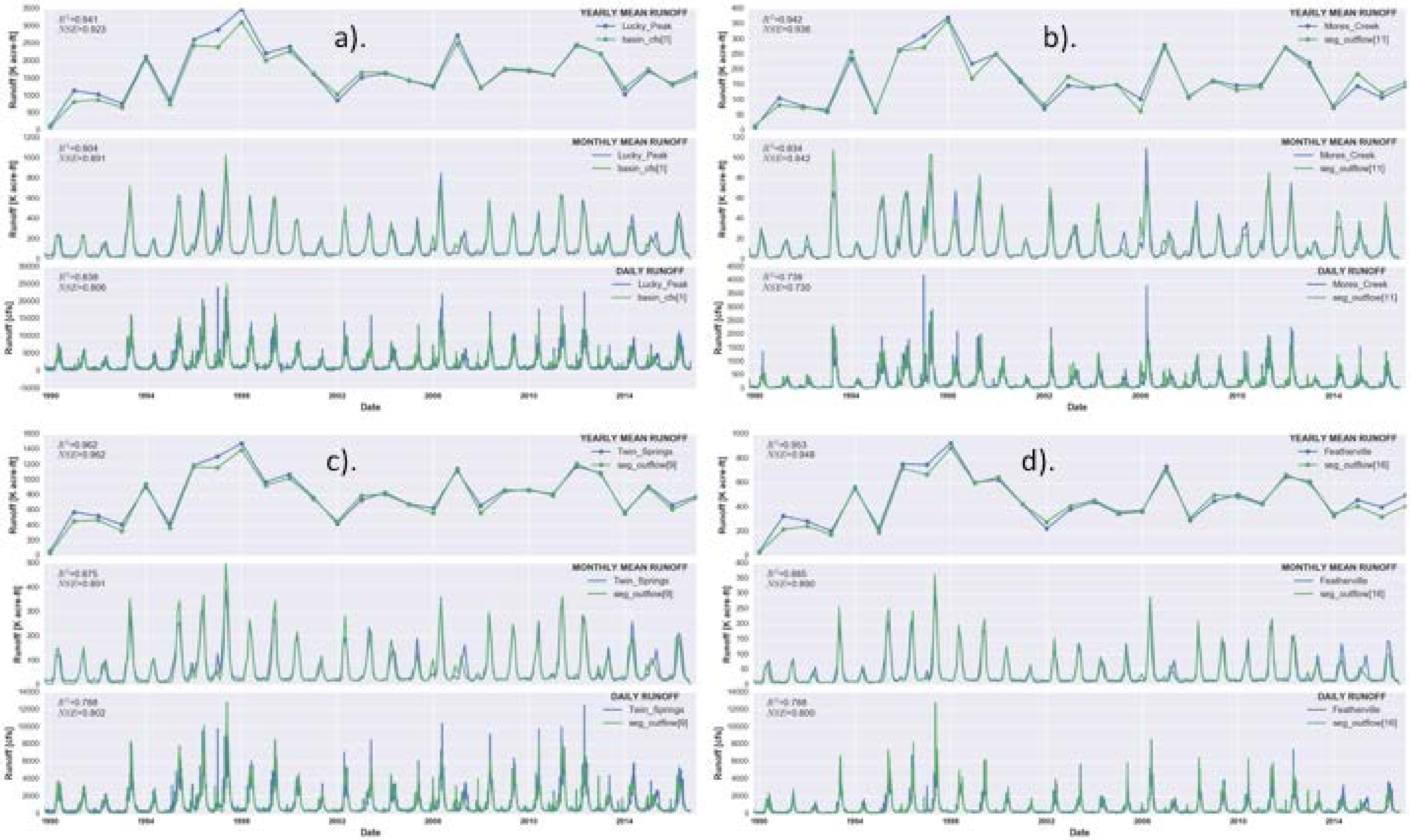


Figure 2. **Calibrated and measured yearly water volume, monthly water volume, and daily runoff for a) Lucky Peak, b) Mores Creek, c) Twin Springs, and d) Featherville.**

SWE Comparison

Evaluation of spatially distributed models can prove problematic, as there are limited spatial measurements of SWE. Point measurements are available through the SNOTEL network but a scale discrepancy exists from the 7 m^2 snow pillow, to the 100 m by 100 m *iSnobal* grid cell, to the HRU scale. However, SNOTEL measurements provide a baseline to compare trends in the snow accumulation and melt period. With the size of the PRMS HRUs we expected the snowpack to be underestimated when compared to a SNOTEL measurement due to the larger area that can contain a large elevation range, aspects, and vegetation types. As compared with the SWE measurements, PRMS underestimated the SWE at all the measurement sites with general trend captured due to large storms (Figure 3 and Figure 4). HRUs that proved problematic, like Bogus Basin and Mores Creek (Figure 3b and d), are HRUs that are in the rain-snow transition zone and further calibration may be necessary to correctly identify the precipitation phase.

The *iSnobal* modeled SWE at the SNOTEL locations match well with the measurements for all years (Figure 3 and Figure 4). The differences could be attributed to local topography within the *iSnobal* domain that accumulates or ablates at a slightly different rate than the SNOTEL location. Within the HRU, the spatial variability becomes apparent with the inter quantile range (IQR) showing a large spread in SWE due to elevational differences and hill slope scale changes in slope and aspect. Looking at a single day of SWE from each model shows the differences in how each model calculates the spatial variability and how the model represents the snowpack over the terrain (Figure 5).

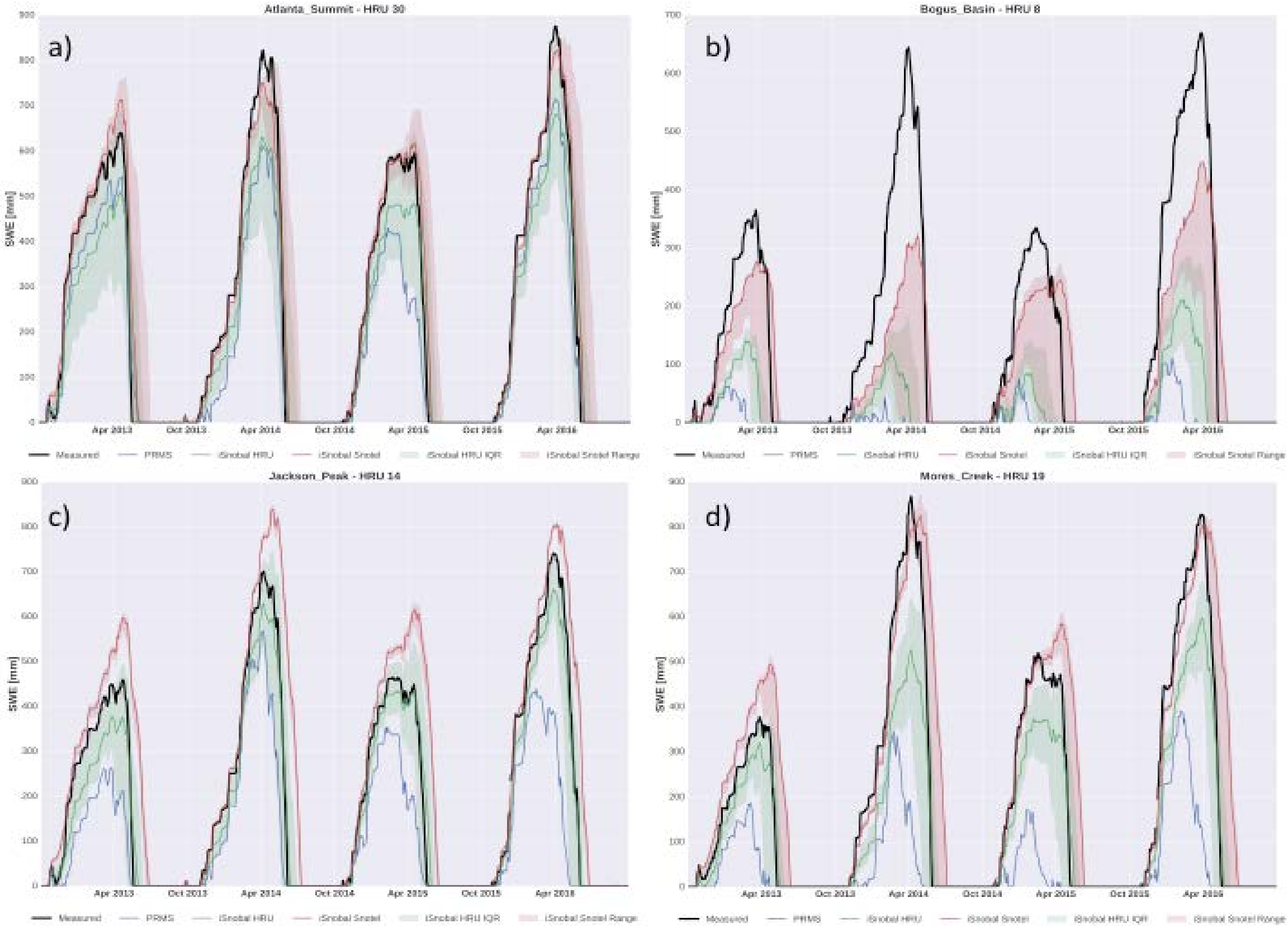


Figure 3.   SWE comparison for Atlanta Summit, Bogus Basin, Jackson Peak, and Mores Creek. Black line is SNOTEL measurement, blue is PRMS, red is 10 *iSnobal* pixels around the measurement, and green is *iSnobal* median and IQR within the HRU.

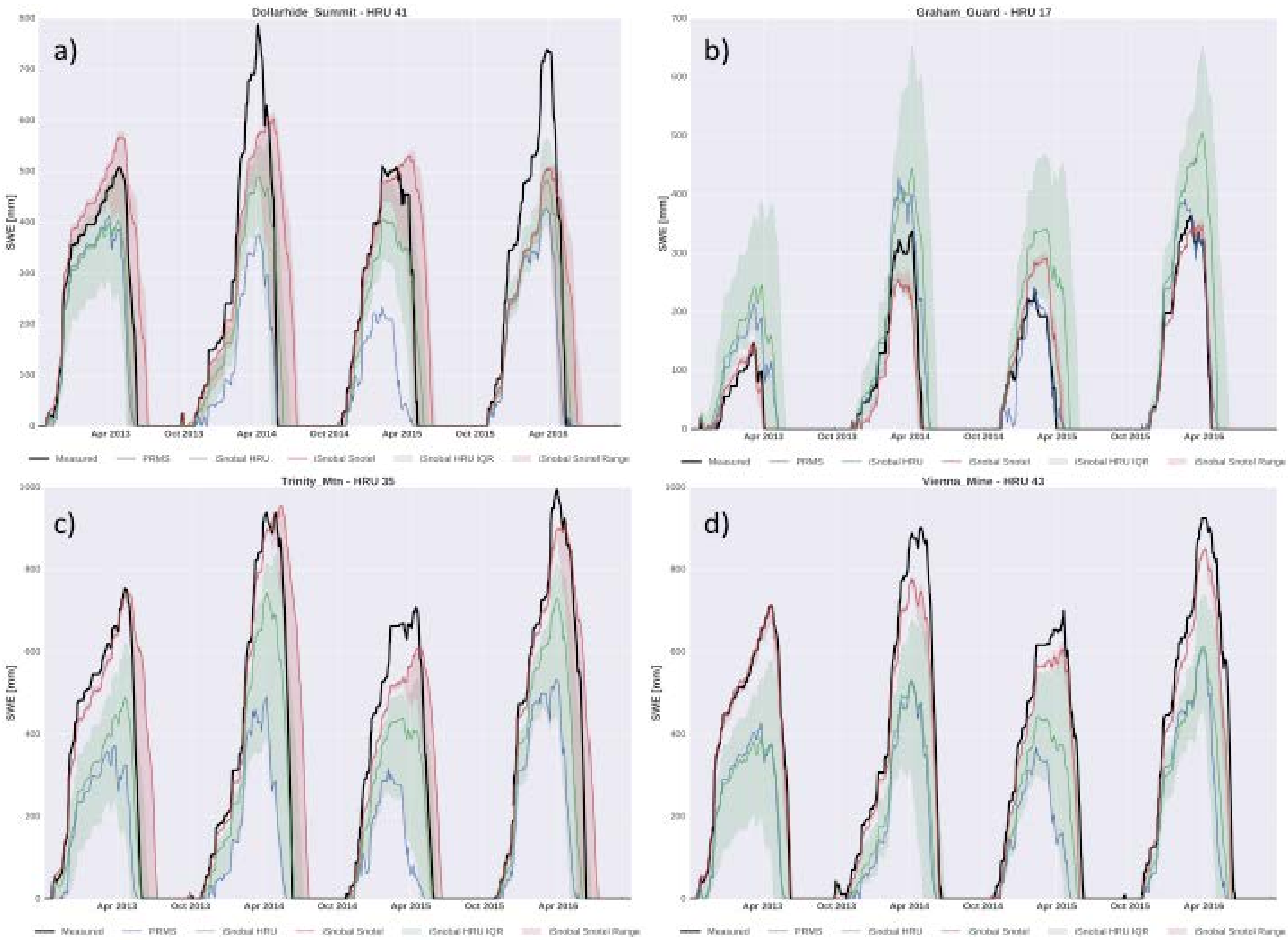


Figure 4. SWE comparison for Dollarhide Summit, Graham Guard Station, Trinity Mountain, and Vienna Mine. Black line is SNOTEL measurement, blue is PRMS, red is 10 *iSnobal* pixels around the measurement, and green is *iSnobal* median and IQR within the HRU.

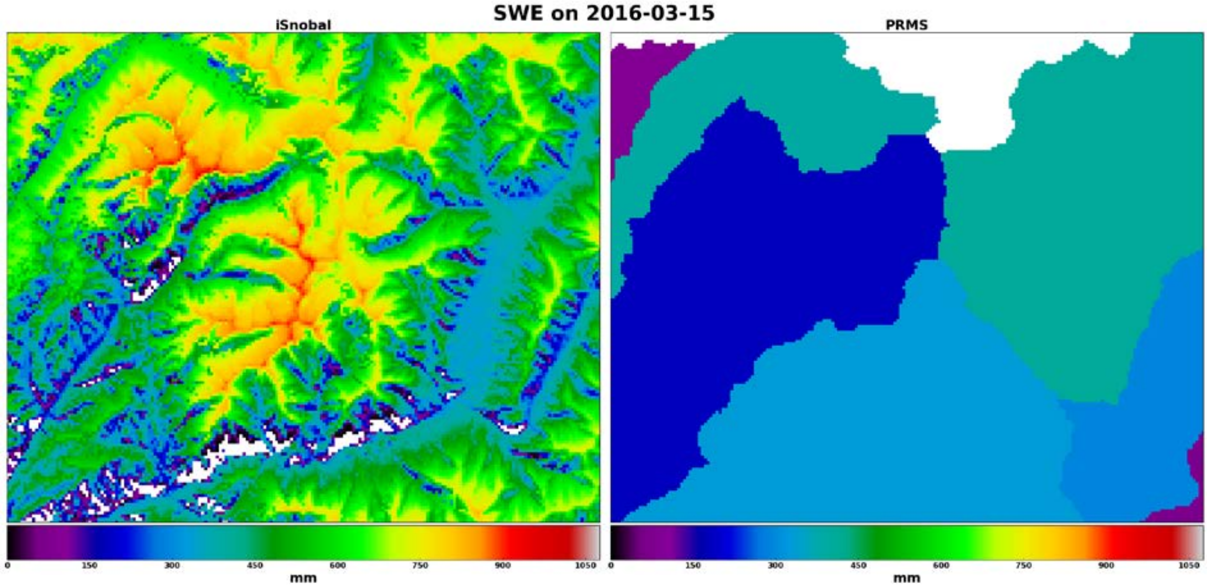


Figure 5. ***iSnobal*** **and PRMS estimated SWE on March 15, 2016 highlighting the differences in the spatial variability and scale between the two models.**

DISCUSSION

The first research question of this project was how model scale affects the underlying physical snow and hydrological processes. *iSnobal* is a high resolution, gridded physically-based model and PRMS is a process-based model that represents the model domain as HRUs. The snowpack in the Boise River basin is a significant component of the hydrologic cycle where winter accumulation and spring snowmelt drive when water is delivered to the system. Comparing SWE estimates from *iSnobal* and PRMS to point measurement shows that PRMS could not accurately reproduce SWE within those HRUs due to the large elevation range and varying topography. The large HRUs were not able to capture the physical processes that were either not represented in the model or occurred at a finer scale than the HRU size. For example, the coarse HRU size cannot capture the physical processes at the hill slope scale or those processes that are elevation dependent.

The manual calibration performed extremely well for yearly and monthly water volumes. A more rigorous calibration of all the other parameters may improve the model results but may still lack the physical representation due to the large HRUs. It is possible to run PRMS with smaller HRUs that capture the elevation and topography, but this comes at a cost of significantly increasing the number of parameters that must be calibrated. For example, tmax_cbh_adj must be calibrated for each HRU, for each month of the year. Currently, there are 1,032 elements to this parameter and increasing the number of HRUs by 4r would increase the number of parameters to 4,128. The increase in parameters further makes the calibration an over-determined problem, increasing the potential for finding a local minimum instead of the global minimum.

Addressing climate change implications requires using models that are robust to climate change. This means using physically-based models that calculate the full energy balance instead of those that parameterize or use empirical functions in lieu of energy balance calculations. Even with robust calibration, for example bootstrap, jack-knife, or leave-on-out techniques, there is a high potential for PRMS to reach a solution but for the wrong reasons. In a future climate change scenario, the model does not accurately represent the physical processes of the basin and will provide a solution that is not accurate.

For future climate change scenarios in snow-dominated basins, models must explicitly calculate the processes that play a major role in snowmelt, like the turbulent transfer of sensible and latent heat. As the climate warms, the rain-snow transition zone will continually rise in elevation, which increases the potential for rain-on-snow events at the lower edge of the snow zone (Kattelmann 1997; Tohver, Hamlet, and Se-Yeun 2014). PRMS does not explicitly calculate the energy balance for rain-on-snow events as *iSnobal* does, indicating that future predications with PRMS will have high uncertainty during such events. Because of how PRMS model represents the snowpack and precipitation phase, the model was unable to capture the large 1997 rain-on-snow flooding event in the Boise River basin. The snow calculations in the course scale models like PRMS must be improved by incorporating the physical processes that govern the energy and mass changes.

The results of the SWE comparison and S&T 2264 and 2157 show the potential to use *iSnobal* as an operational tool and how *iSnobal* can also address potential climate change scenarios. Since *iSnobal* explicitly calculates the snowcover mass and energy balance, the model is robust to climate variation and change and would be able to answer questions about how a warmer climate would affect the snow accumulation and melt for reservoir operations.

CONCLUSIONS

The coupling of *iSnobal* and PRMS is an area of active development and this project gave ARS the necessary foundation to move forward. By working with both DHSVM and PRMS, we have found that full physically-based hydrology models may not be feasible due to the significant number of physical parameters required. On the other hand, overly simplistic models like PRMS that only represent approximations, will result in the process requiring additional physics to accurately represent the snowpack energetics. Even with robust calibration of these simplistic, parameterized models, the robustness of PRMS to climate change will rely solely on the estimates of the mass and energy balance, which may not hold true under a changing climate. Therefore, over the next couple of years, ARS will be working with Reclamation, National Aeronautics and Space Administration – Jet Propulsion Laboratory, NRCS, and California DWR to couple *iSnobal* to the water routing components of PRMS, which will provide a new tool to lower the uncertainty for real time operational use, but also address how a change in the rain-snow transition elevation, and an expected increase in rain-on-snow events may affect the management decisions under a changing climate.

References

Parenthetical Reference	Bibliographic Citation
Brekke, Kuepper, and Vaddy 2010	Brekke, L., B. Kuepper, and S. Vaddy. 2010. “Climate and Hydrology Datasets for Use in the RMJOC Agencies’ Longer-Term Planning Studies: Part I - Future Climate and Hydrology Datasets.” Bureau of Reclamation, U.S. Army Corps of Engineers, Bonneville Power Administration. https://www.usbr.gov/pn/climate/planning/reports/part1.pdf.
Garen and Marks 1996	Garen, David, and Danny Marks. 1996. “Spatially Distributed Snow Modelling in Mountainous Regions: Boise River Application.” In HydroGIS 96: Application of Geographic Information System in Hydrology and Water Resources Management (Proceedings of the Vienna Conference).
Garen and Marks 2005	Garen, David, and Danny Marks. 2005. “Spatially Distributed Energy Balance Snowmelt Modelling in a Mountainous River Basin: Estimation of Meteorological Inputs and Verification of Model Results.” Journal of Hydrology 315 (1–4): 126–153. doi:10.1016/j.jhydrol.2005.03.026.–91. doi:10.1111/j.1752-1688.1994.tb03307.x.
Havens et al. 2015	Havens, Scott, Danny Marks, Adam Winstral, and Eric Rothwell. 2015. “Application of a Physically-Based Distributed Snowmelt Model in Support of Reservoir Operations and Water Management, {ST-2015-2264}.”
Havens et al. InReview	Havens, Scott, Danny Marks, Patrick Kormos, and Andrew Hedrick. InReview. “Spatial Modeling for Resources Framework (SMRF): A Modular Framework for Developing Spatial Forcing Data for Natural Resources Modeling Applications.” Computers and Geosciences. gitlab.com/ars-snow/smrf.
Havens, Marks, and Rothwell 2016	Havens, Scott, Danny Marks, and Eric Rothwell. 2016. “Application of a Physically-Based Distributed Snowmelt Model in Support of Reservoir Operations and Water Management, {ST-2016-2157-1}.” http://www.usbr.gov/research/projects/detail.cfm?id=2157.
Hay et al. 2006	Hay, Lauren E., George H. Leavesley, Martyn P. Clark, Steve L. Markstrom, Roland J. Viger, and Makiko Umemoto. 2006. “Step Wise, Multiple Objective Calibration of a Hydrologic Model for a Snowmelt Dominated Basin.” Journal of the American Water Resources Association 42 (4): 877–890. doi:10.1111/j.1752-1688.2006.tb04501.x.

Parenthetical Reference	
Hay and Umemoto 2006	Hay, Lauren E., and M. Umemoto. 2006. “Multiple-Objective Stepwise Calibration Using Luca.” 2006–1323.
Homer et al. 2015	Homer, C.G., J.A. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N.D. Herold, J.D. Wickham, and K. Megown. 2015. “Completion of the 2011 National Land Cover Database for the Conterminous United States-Representing a Decade of Land Cover Change Information.” Photogrammetric Engineering and Remote Sensing 81 (5): 345–354.
Horel et al. 2002	Horel, J, M. Splitt, L. Dunn, J. Pechmann, B. White, C. Ciliberti, S. Lazarus, J. Slemmer, D. Zaff, and J. Burks. 2002. “Mesowest: Cooperative Mesonets in the Western United States.” Bull. Amer. Meteor. Soc. 83 (2): 211–225. doi:10.1175/1520-0477(2002)083<0211:MCMITW>2.3.CO;2.
Kattelmann 1997	Kattelmann, Richard. 1997. “Flooding from Rain-on-Snow Events in the Sierra Nevada.” IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences 239: 59–66.
LANDFIRE 2016	LANDFIRE. 2016. “Existing Vegetation Type, Height, and Cover, LANDFIRE 1.4.0, U.S. Department of the Interior, Geological Survey.” Accessed October 1. http://landfire.cr.usgs.gov/viewer/.
Leavesley et al. 1983	Leavesley, G.H., R W. Lichty, B.M. Troutman, and L.G. Saindon. 1983. “Precipitation Runoff Modeling System: User’s Manual.” U.S. Geological Survey Water Resources Investigation Report 83–4238, 207.
Marks et al. 1999	Marks, Danny, James Domingo, Dave Susong, Tim Link, and David Garen. 1999. “A Spatially Distributed Energy Balance Snowmelt Model for Application in Mountain Basins.” Hydrological Processes 13 (February): 1935–1959.
Markstrom et. 2015	Markstrom, Steven L., Steven Regan, Lauren E. Hay, Roland J. Viger, Richard M.T. Webb, Robert A. Payn, and Jacob H. LaFontaine. 2015. “PRMS-IV the Precipitation-Runoff Modeling System, Version 4.” U.S. Geological Survey Techniques and Methods, Book 6: Modeling Techniques, Chap. B7, 158. doi:http://dx.doi.org/10.3133/tm6B7.

	Bibliographic Citation
Nash and Sutcliffe 1970	Nash, J E, and J V Sutcliffe. 1970. "River Flow Forecasting Through Conceptual Models Part I-a Discussion of Principles*." Journal of Hydrology 10: 282–290. doi:10.1016/0022-1694(70)90255-6.
NRCS 2016	Natural Resources Conservation Service, Soil Survey Staff. United States Department of Agriculture. 2016. " Web Soil Survey." Accessed October 1. http://websoilsurvey.nrcs.usda.gov/.
Tohver and Se-Yeun 2014	Tohver, I.M., A.F. Hamlet, and L. Se-Yeun. 2014. "Impacts of 21st-Century Climate Change on Hydrologic Extremes in the {Pacific Northwest Region of North America}." Journal of the American Water Resources Association 50 (6): 1461–1476.
Wigmosta, Vail, and Lettermaier 1994	Wigmosta, M S, L. Vail, and Dennis P. Lettenmaier. 1994. "A Distributed Hydrology-Vegetation Model for Complex Terrain." Water Resources Research 30: 1665–1679.

APPENDICES

USDA ARS has included all the necessary files for running PRMS, including the data files, parameter files, and control files. The shapefile with the HRU delineations and initial parameters are also included.

The input data for *iSnobal* is also included. This is 4 years of the necessary point data required for distributing the forcing data. SMRF version 0.1.0 was used with the configuration files included. *iSnobal* in IPW version 2.2.0.

If further data is required, please contact USDA ARS Boise for further assistance.