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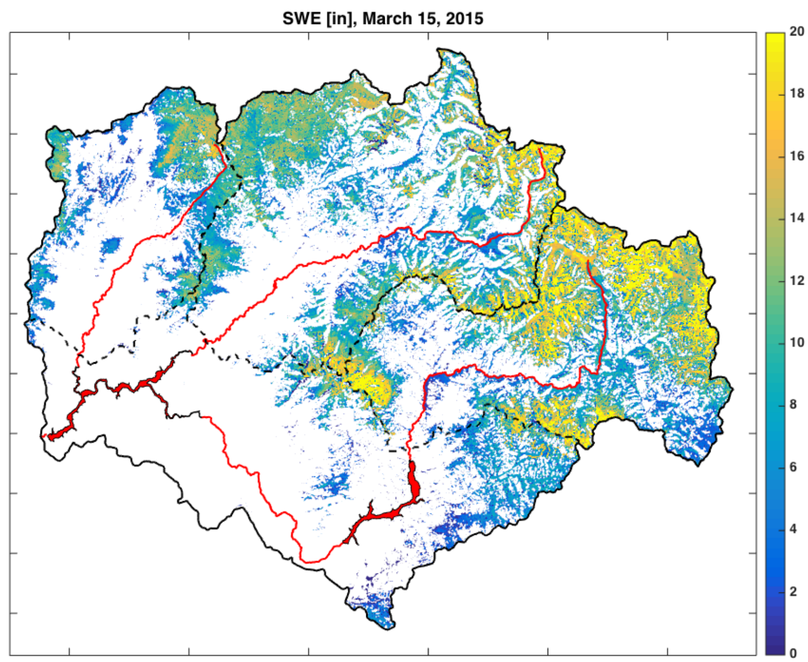
Managing Water in the West

Application of a Physically-based Distributed Snowmelt Model in Support of Reservoir Operations and Water Management

Research and Development Office
Science and Technology Program
Final Report ST-2015-2264-1



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

September 2015

U.S. DEPARTMENT OF THE INTERIOR

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REPORT DOCUMENTATION PAGE		*Form Approved OMB No. 0704-0188*
T1. REPORT DATE April 2015	**T2. REPORT TYPE Research**	**T3. DATES COVERED** FY13-FY15
T4. TITLE AND SUBTITLE Application of a Physically-based Distributed Snowmelt Model in Support of Reservoir Operations and Water Management		**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 Adam Winstral, awinstral@gmail.com Eric Rothwell, 208-378-5370 erothwell@usbr.gov		**5d. PROJECT NUMBER** 2264 **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)*
Current operational snowmelt models to drive streamflow forecasts rarely contain a physical foundation and have been shown to be unreliable in non-normal conditions. In contrast, physically based, distributed models are robust to non-normal conditions and have the potential to improve reservoir management decisions by providing distributed snowpack properties. This project focused on applying the physically based, distributed snow model *iSnobal* in an operational setting by running the model in near real time. Snowpack results, such as spatially distributed snow water equivalent (SWE), susceptibility to melt, and the volume of liquid water delivered to the soil (snow melt or rain) were provided on a weekly basis for water years 2013 to 2015 to local area water managers. In 2015, *iSnoba*l was loosely coupled to a hydrologic routing model and a short term weather forecasting model. The coupling provided a proof of concept 3-day streamflow forecast by using the weather forecast to drive the snow model and route melt water to the stream channels.

15. SUBJECT TERMS
Examining the effects of reservoir operations on bull trout in the Deadwood Reservoir using data collected from the reservoir to calibrate and validate a combined physical-chemical and biological model to describe reservoir conditions using different reservoir operation scenarios.

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: Application of a Physically-based Distributed Snowmelt Model in Support of Reservoir Operations and Water Management

WOID:

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

Document date:

Peer Reviewer: David Garen

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 David G. Garen Date Reviewed: 8. October 2015
(Signature)

Executive Summary

Current operational snowmelt models to drive streamflow forecasts rarely contain a physical foundation and have been shown to be unreliable in non-normal conditions. In contrast, physically-based, distributed models are robust to non-normal conditions and have the potential to improve reservoir management decisions by providing distributed snowpack properties. This project focused on applying the physically-based, distributed snow model *iSnobal* in an operational setting by running the model in near real time. Snowpack results, such as spatially distributed snow water equivalent (SWE), susceptibility to melt, and the volume of liquid water delivered to the soil (snow melt or rain) were provided on a weekly basis for water years 2013 to 2015 to local area water managers. In 2015, *iSnobal* was loosely coupled to a hydrologic routing model and a short-term weather forecasting model. The coupling provided a proof of concept 3-day streamflow forecast by using the weather forecast to drive the snow model and route melt water to the stream channels.

Acronyms and Abbreviations

BSU	Boise State University
DHSVM	Distributed Hydrology Soil Vegetation Model
ET	evapotranspiration
JPL	Jet Propulsion Laboratory
km^2	square kilometers
m	meter
mm	millimeters
NRCS	Natural Resources Conservation Service
NWRFC	Northwest River Forecast Center
PRISM	Precipitation- elevation Regressions on Independent Slopes Model)
PRMS	Precipitation Runoff Modeling System
RCEW	Reynolds Creek Experimental Watershed
Reclamation	U.S. Bureau of Reclamation
S&T	Science and Technology
SWE	Snow water equivalent
SWI	Snow water input
USDA-ARS	U.S. Department of Agriculture, Agricultural Research Service
USGS	U.S. Geological Survey
WRF	Weather Research and Forecasting
WY	water year

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PROJECT SUMMARY

Current operational snowmelt driven streamflow forecasts are typically derived from statistical relationships largely based on a combination of historic trends and calibrations to point observations of snow water equivalent (SWE) or as-available satellite observations of snow covered areas. These models rarely contain a physical basis and have been shown to become unreliable when non-normal conditions are encountered (Brekke et al. 2010). Physically-based, distributed models require little to no calibration and are forced using only current and predicted conditions. The physical basis means that all mass and energy fluxes that affect the snow cover are numerically calculated from the governing physics. These models are robust to non-normal climate conditions and ideal tools for evaluating streamflow responses to short-term extreme events such as rain-on-snow, the extended effects of unseasonable wet, dry, warm, or cold periods, and the long-term effects of climate warming.

Project Goals

The project goal was broken down into three stages:

1. Application of *iSnobal* using currently available data from meteorological stations in an operational setting where present snow and melt conditions are updated on a short time interval to provide relevant information for river system operations

2. Couple *iSnobal* to a soil storage and routing model to convert the *iSnobal* modeled surface water input to stream discharge

3. Proof of concept to couple the *iSnobal*-routing model to a short-term weather forecast to provide 1 to 3 day reservoir inflows

Products

For water year (WY) 2013 to WY 2015, the U.S. Department of Agriculture – Agricultural Research Service (USDA-ARS) provided weekly snowpack updates to the Bureau of Reclamation (Reclamation) from roughly peak SWE through the snow melt season. The reports provided information on the spatial distribution of SWE and the surface water input (SWI) or volume of liquid water delivered to the soil surface. In WY 2015, the reports were distributed to all interested water managers including Reclamation, Idaho Water Supply Committee, Northwest River Forecast Center (NWRFC), Idaho Power, Natural Resource Conservation Service (NRCS), local water district managers, U.S. Forest Service (USFS), Utah Water Research Laboratory, and NASA-Jet Propulsion Laboratory (JPL). The proof of concept coupling of three physically-based models provided a 3-day reservoir inflow forecast to Reclamation that was shared with NWRFC.

STUDY AREA AND OPERATIONAL SIGNIFICANCE

The Boise River, a tributary of the Snake River in Southwest Idaho, has three forks that drain the Boise, Soldier, Sawtooth, and Smokey mountains. The Boise River flows through Boise and several smaller communities, comprising the largest population center for the state. Upstream of this population center, 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. Since 1950, the Boise projects have prevented over $1.5 billion dollars in flood damages locally and downstream (Reclamation 2014). Reclamation water managers need accurate knowledge of snow and runoff generation within the basin to provide irrigators water throughout the summer and prevent potential flooding downstream. 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 et al. 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. Because 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.

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 Boise River basin ranges in elevation from 858 meters near the outlet to 3187 meters at its highest point. Due to the large range in elevation, the basin has a multitude of land covers, comprised of forest (43%), shrub land (35%), herbaceous (21%), and other land covers (1%). 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.

There are 18 meteorological stations in and around the basin used for near real time modeling and 3 stream gauges (Figure 1). Ten of the stations are from the Natural Resources Conservation Service (NRCS) SNOTEL network and provide precipitation, air temperature, and snow water equivalent with three sites measuring solar radiation and five sites measuring relative humidity. The other eight stations are from the Mesowest network and are owned by Reclamation, Bureau of Land Management, and the Sawtooth Avalanche Center. Mesowest instrumentation is site-dependent. These stations measure a combination precipitation, air temperature, relative humidity, solar radiation, and wind.

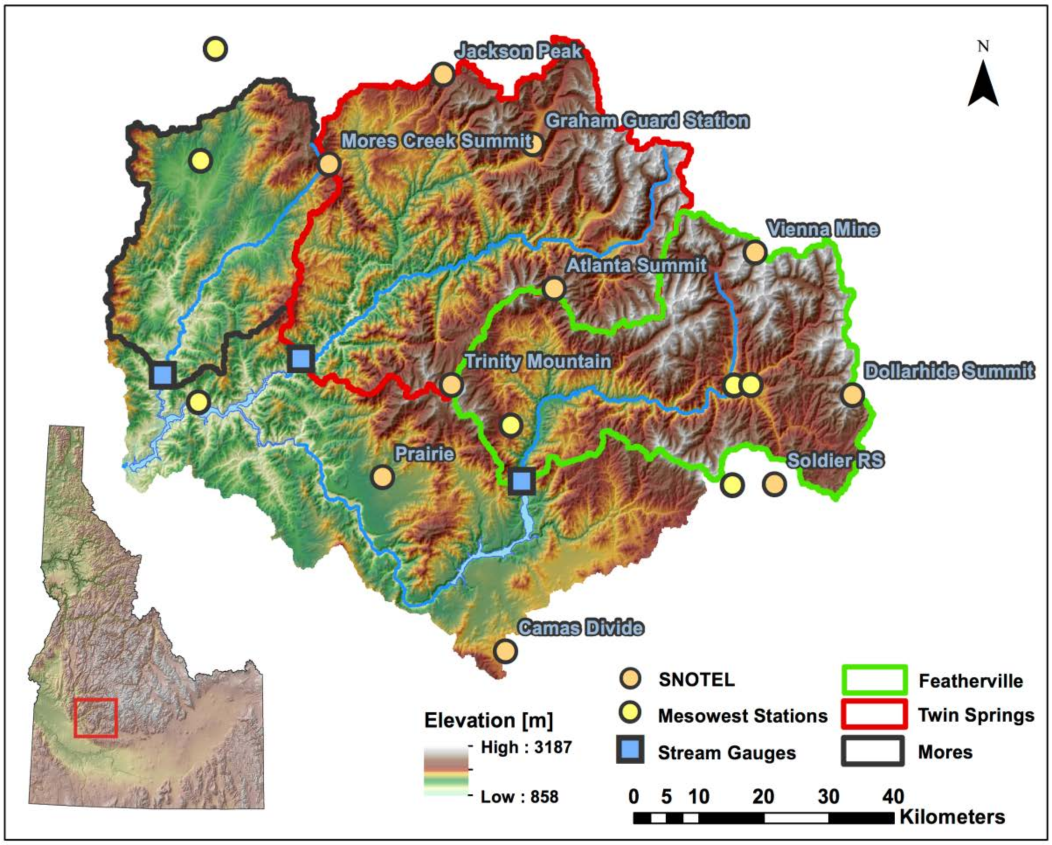

Figure 1. Boise River basin with subbasins Mores Creek, Twin Springs, and Featherville (left to right). SNOTEL, Mesowest stations, and stream gauges used to derived spatial fields and validation data are shown.

MODEL DESCRIPTIONS

iSnobal

The physically-based distributed snowmelt model *iSnobal* (Marks et al. 1999) is a DEM grid-based energy and water balance model. *iSnobal* models the snowpack as two-layers, with the active surface layer exchanging energy with the atmosphere and the lower layer transferring energy between the surface and soil layer (Figure 2). The snow temperature, density, and liquid water content are solved for each layer. *iSnobal* forcing data inputs are raster surfaces over the DEM grid of incoming thermal (long-wave) radiation, air temperature, vapor pressure, wind speed, soil temperature, net solar radiation, and precipitation. Given the forcing data inputs, the energy balance, snow temperature, and cold content (the energy required to bring the snow to 0˚Celsius (C) are computed for each grid cell. Melt cannot occur until the temperature of the snow cover is at 0˚C, where the cold content equals 0.

Liquid water drainage from the snow does not occur until the liquid water holding capacity of the snow is exceeded.

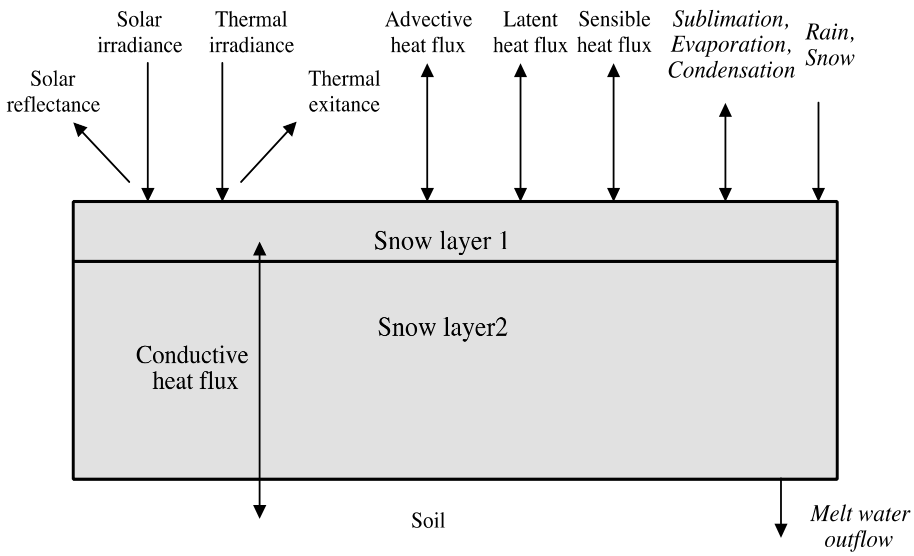

Figure 2. ***iSnobal* snowpack diagram with energy and mass fluxes (italics) (Garen and Marks 2005).**

Numerous research studies have applied *iSnobal* in various settings. These studies recreate the snowpack for past years using carefully quality controlled meteorological data and compare with snow surveys or other measurements. Winstral and Marks (2002) coupled wind and wind-affected snow distribution techniques with *iSnobal*. This modeling combination captured highly heterogenic snow accumulation and melt patterns vital to accurately predicting streamflow in research basins (0.27 – 14.1 km^2) throughout the Reynolds Creek Experimental Watershed (RCEW) in southwestern Idaho (Winstral et al. 2013). Reba et al. (2011) ran the aforementioned *iSnobal* product at one of these RCEW research watersheds for a 25-year period demonstrating the robustness of *iSnobal* to conditions ranging from dry to wet and warm to cold. *iSnobal* has also been successfully applied across a range of spatial scales (0.04 – 300 km^2) in southwestern Idaho (Kormos et al. 2014), Canadian Boreal Forest (Link and Marks 1999), Oregon Cascades (Mazurkiewicz et al. 2008), Sierra Nevada, California (Kahl et al. 2013; Marks et al. 1999), and the Wasatch mountains of Utah (Marks et al. 1999). An early test demonstrating the potential of *iSnobal* for operational river basin applications was conducted in the Twin Springs subbasin (2,150 km^2) of the Boise River (Garen and Marks 2005). In the Twin Springs application, distributed model forcings across a 250 meter (m) resolution grid were derived from readily available meteorological observations and modeling was conducted at a 3-hour time step. Though both the time and spatial domains were very coarse, the results were surprisingly accurate.

The forcing data for *iSnobal* were derived from 18 meteorological stations in and around the Boise River basin. *iSnobal* requires distributed forcings of air temperature, precipitation, dew point temperature, wind speed, solar, and thermal radiation at hourly time steps. Air temperature and precipitation were distributed using a downscaled PRISM (Precipitation-elevation Regressions on Independent Slopes Model) (Daly et al. 1994) product based on the PRISM cell elevation and distance to the surrounding stations. PRISM-derived precipitation distribution was then modulated to account for wind redistribution and drifting after the work of Winstral et al. (2009, 2013, 2014). Other forcing data were distributed using an inverse weighting scheme based on distance and elevation.

Distributed Hydrology Soil Vegetation Model

The Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al. 1994) provides a spatial representation of physical watershed processes over a DEM. The model accounts for all atmosphere-surface mass and energy exchanges affecting hydrologic responses and includes surface and sub-surface water routing schemes. DHSVM is a complete hydrologic model that tracks water from precipitation inputs through the vegetation canopy to the soil surface accounting for interception and evapotranspiration, vertically and laterally through the soil column or over the land surface if infiltration rates have been exceeded or the water table intersects the soil surface, to the channel network, and then through the stream system on a reach-by-reach basis. DHSVM also includes a snowmelt module as well as hard-coded elevation and distance weighted routines for distributing point meteorological observations.

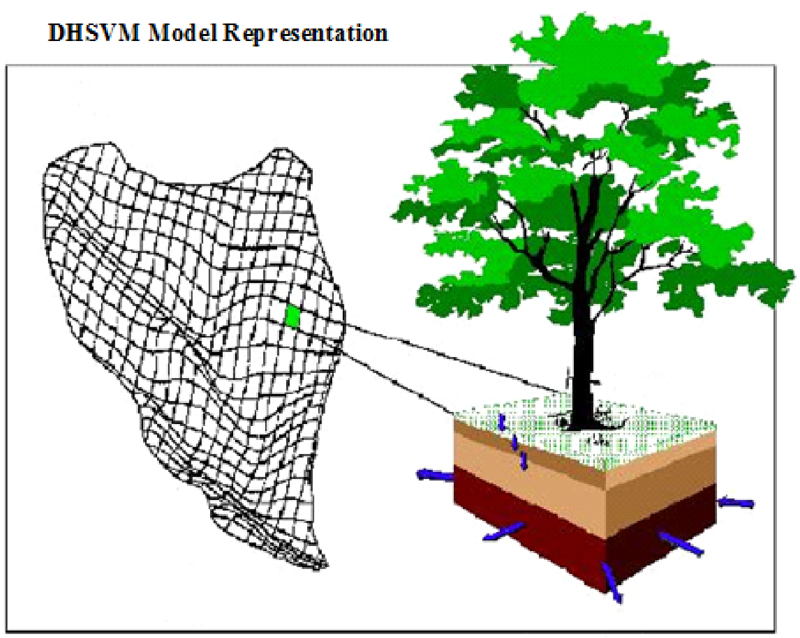

Figure 3. DHSVM model representation based on a DEM grid. Grid cells exchange water with neighbors until the water is routed to the stream (adapted from Wigmosta et al. 1994).

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 DHSVM modules were used to route *iSnobal* surface water inputs into and through the stream system to simulate streamflows. This approach was taken to facilitate the inclusion of the wind-affected snow distributions already paired with *iSnobal*, and increased the options available for distributing the point meteorological observations. Stream simulations are currently only produced through late spring.

Weather Research and Forecasting

The Weather Research and Forecasting (WRF) model is a mesoscale numerical weather prediction system used for both research and operational forecasting.[1] WRF can model weather at a range of spatial resolutions from tens of meters to hundreds of kilometers, but because of the numerical complexity, is limited to about 1 km^2, and 2 to 3 km^2 is more typical. WRF was designed for down scaling of global atmospheric model outputs, but can also ingest surface data. It generates atmospheric simulations based on initial conditions derived from a combination of surface data or idealized conditions from global atmospheric models.

Boise State University (BSU) provided daily WRF-generated 3-day forecasts at a 3 km resolution (Science and Technology [S&T] Project 9682). The WRF outputs (Figure 4) of air temperature, relative humidity, wind speed, precipitation, cloud fraction and long wave radiation are downscaled for inputs to *iSnobal*. For development and proof of concept purposes, the downscaling method was bi-linear interpolation commonly used to downscale WRF outputs. The downscaled WRF outputs were used as forcing data inputs to *iSnobal* to produce melt and SWI that DHSVM routed to streamflow. The loose coupling of the 3 models provided a 3-day forecast of streamflow into the 3 main Reclamation reservoirs.

[1] Available online: http://www.wrf-model.org/index.php

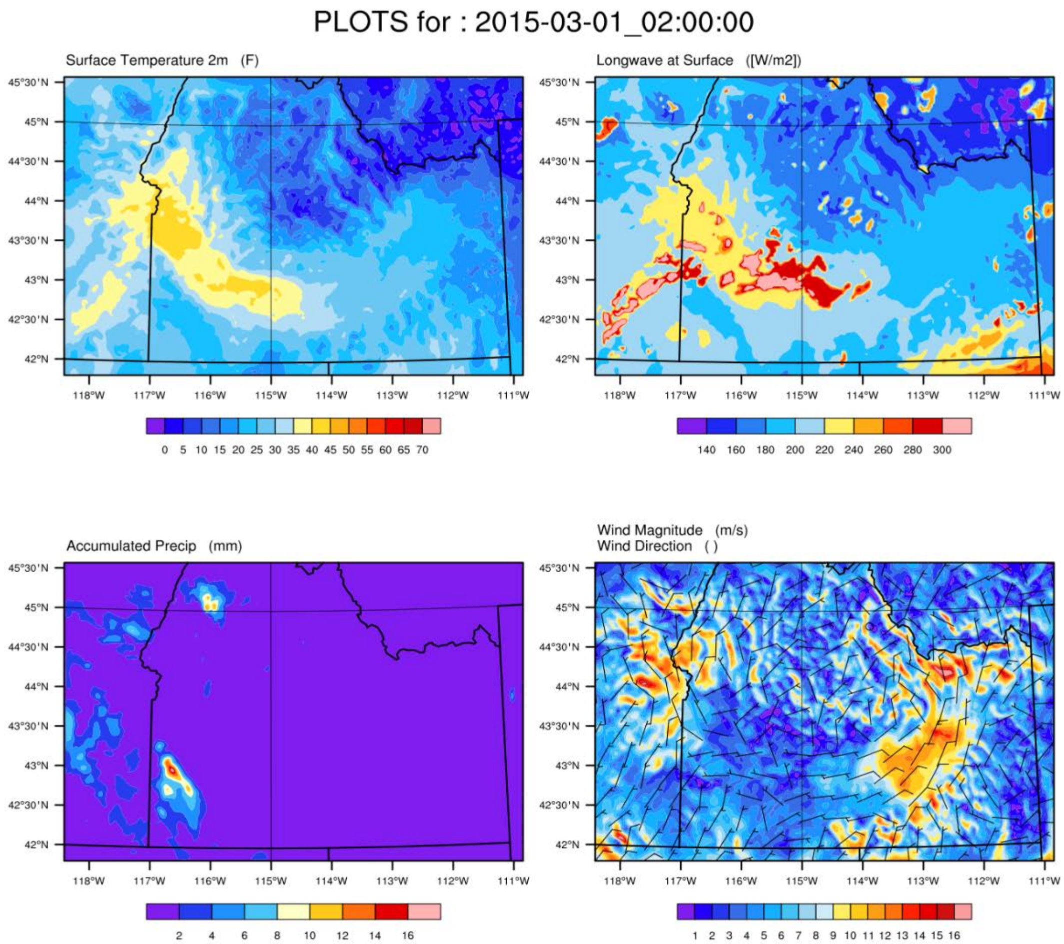

Figure 4. WRF domain outputs for surface temperature, longwave, precipitation, and wind. These outputs were downscaled to the Boise River basin domain resolution.

REAL TIME MODELING

iSnobal was initiated on October 1 at the beginning of the water year by downloading all the required forcing data from weather stations, distributing the forcing data over a 100 m DEM, and running *iSnobal* at an hourly time resolution. Once the spin up was complete to the current date, *iSnobal* was run at weekly intervals by downloading the past week's weather station data, distributing the forcing data, and running *iSnobal*. Real time modeling typically began in March at a time of approximately peak SWE and prior to the typical initiation of spring snowmelt.

Water Year 2013 and 2014

WY 2013 and WY 2014 were the first application of *iSnobal* in an operational setting for a basin of this size. Therefore, new techniques and procedures were developed to reduce the amount of time spent downloading weather station data and deriving spatial forcing fields. The first 2 years of the project, weekly maps of the Boise River basin SWE and cold content were sent to Reclamation water managers (Figure 5). In addition to providing physically-driven snow state results the spatially distributed models like *iSnobal* provide useful information on how much SWE is in the basin, where it is and how susceptible it is to melting. Charts of SWE for different elevations utilize the high-resolution spatial information from the model (Figure 6).

While weekly *iSnobal* results were generated in WY 2013 and WY 2014, the coupling of *iSnobal* to a water routing model was under development.

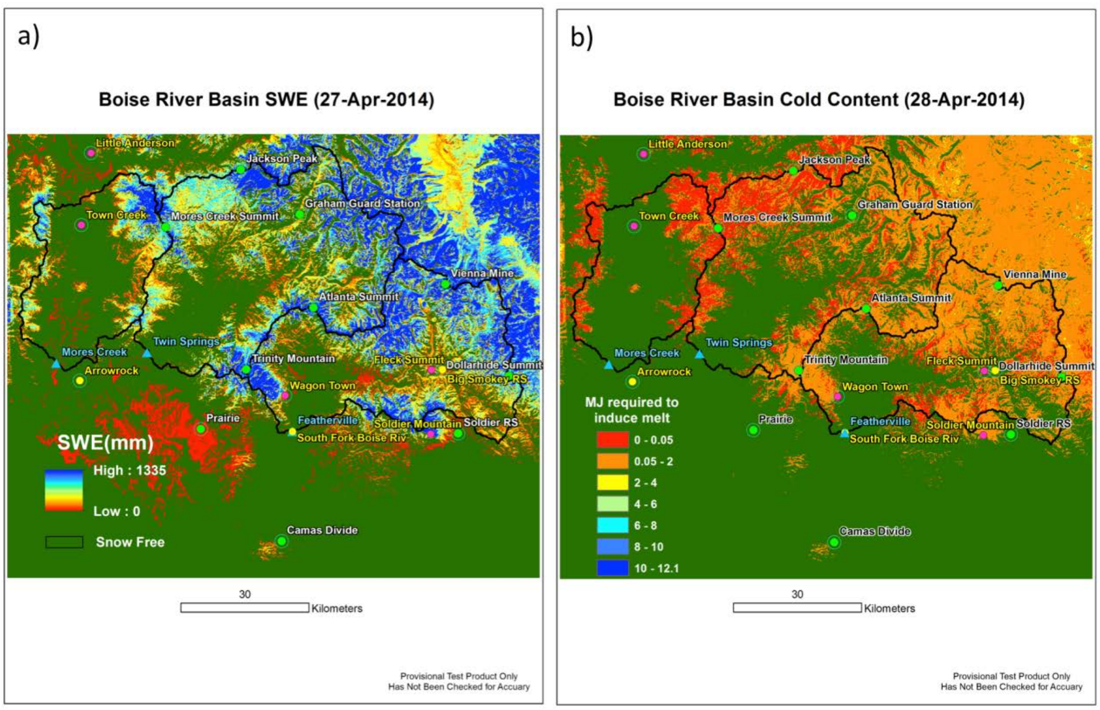

Figure 5. An example of a weekly *iSnobal* modeled SWE and cold content maps sent to Reclamation.

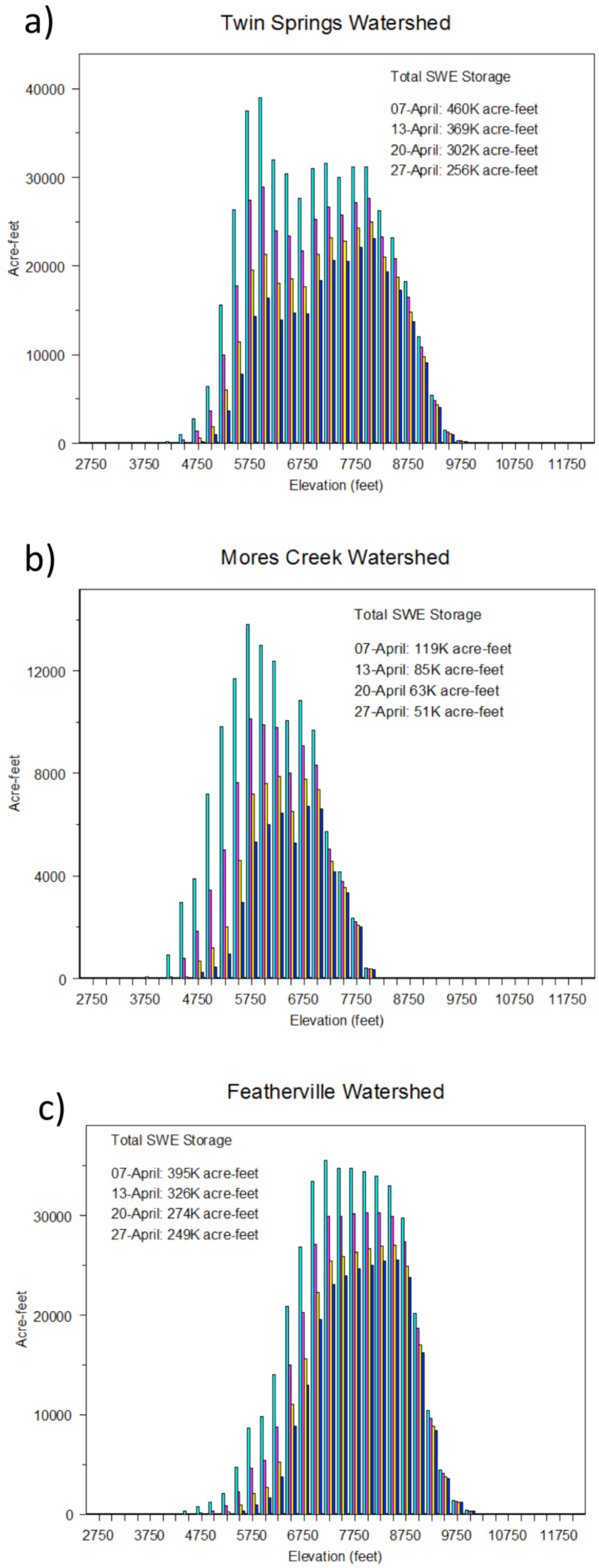

Figure 6. An example of modeled SWE versus elevation by subbasin, useful for demonstrating snow distribution by elevation band.

Water Year 2015

WY 2015 was warmer than average and had a higher than normal rain snow transition zone. Though precipitation through March was 99 percent of normal in the Boise River basin, the snowpack was 67 percent of normal by March and melted more than a month early. Reports to Reclamation began in early March because of the very abnormal conditions and the warmer temperatures. Local water managers and users expressed increasing interest in USDA-ARS snowpack updates due to the abnormally warm spring and resulting atypical snowpack. A short and concise report was generated on a weekly basis to address the past weeks weather, current model results, weekly changes, and the estimated water volumes for the Boise River basin. See Appendix A – Example weekly report for an example of the distributed weekly report.

A proof of concept product was developed to test the ability in coupling the *iSnobal*-routing model to a short-term weather forecast to produce 1-to-3-day reservoir inflow forecasts. Hourly forcing data for *iSnobal* was derived from WRF model output, which in turn forces the routing components of DHSVM. Preliminary results developed a workflow that showed the three models could be coupled to produce a forecasted streamflow (Figure 7).

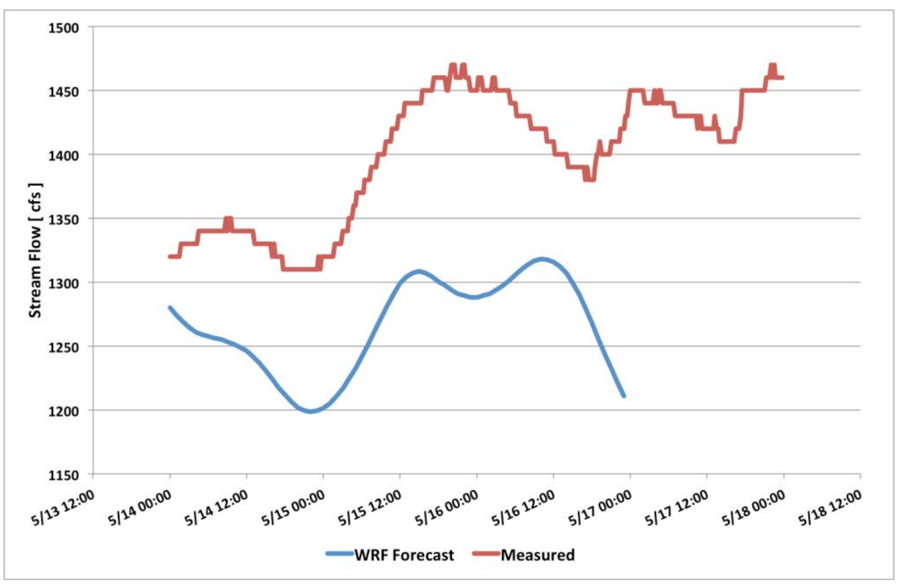

Figure 7. Proof of concept example of a 3-day streamflow forecast from the coupled *iSnobal* routing WRF.

MODEL VALIDATION

Precipitation and Snow Distribution

The initial distribution of precipitation and redistribution of snow is the cornerstone upon which this analysis is based. Since the actual distribution is very complicated (i.e., Winstral and Marks 2002; Winstral et al. 2014) due to wind redistribution, drifting and spatially variable melting, it is the most difficult parameter to estimate, and – short of weekly LiDAR overflights – nearly impossible to validate.

While we cannot know the exact distribution of precipitation, we do know that the volume must exceed basin outflow to account for the 300 to 700 mm of evapotranspiration (ET) that will be used by the forests and vegetation within the basin. The distributed precipitation and measured streamflows, normalized to basin area, for three different subbasins are shown in Figure 8 for WY 2013 to 2015.

Mores basin saw the smallest ratio of runoff to precipitation, with ratios between 0.15 and 0.34. Twin Springs basin saw the largest ratio of runoff to precipitation, with ratios between 0.41 and 0.66. The Featherville basin saw runoff to precipitation ratios between 0.37 and 0.52. In WY 2013, each basin experienced the lowest runoff ratios for each basin and WY 2014 saw largest runoff ratios due to the increased streamflow from intense summer thunderstorms in the area. The runoff ratios show that enough precipitation was distributed to potentially account for ET and streamflow from the Boise River basin.

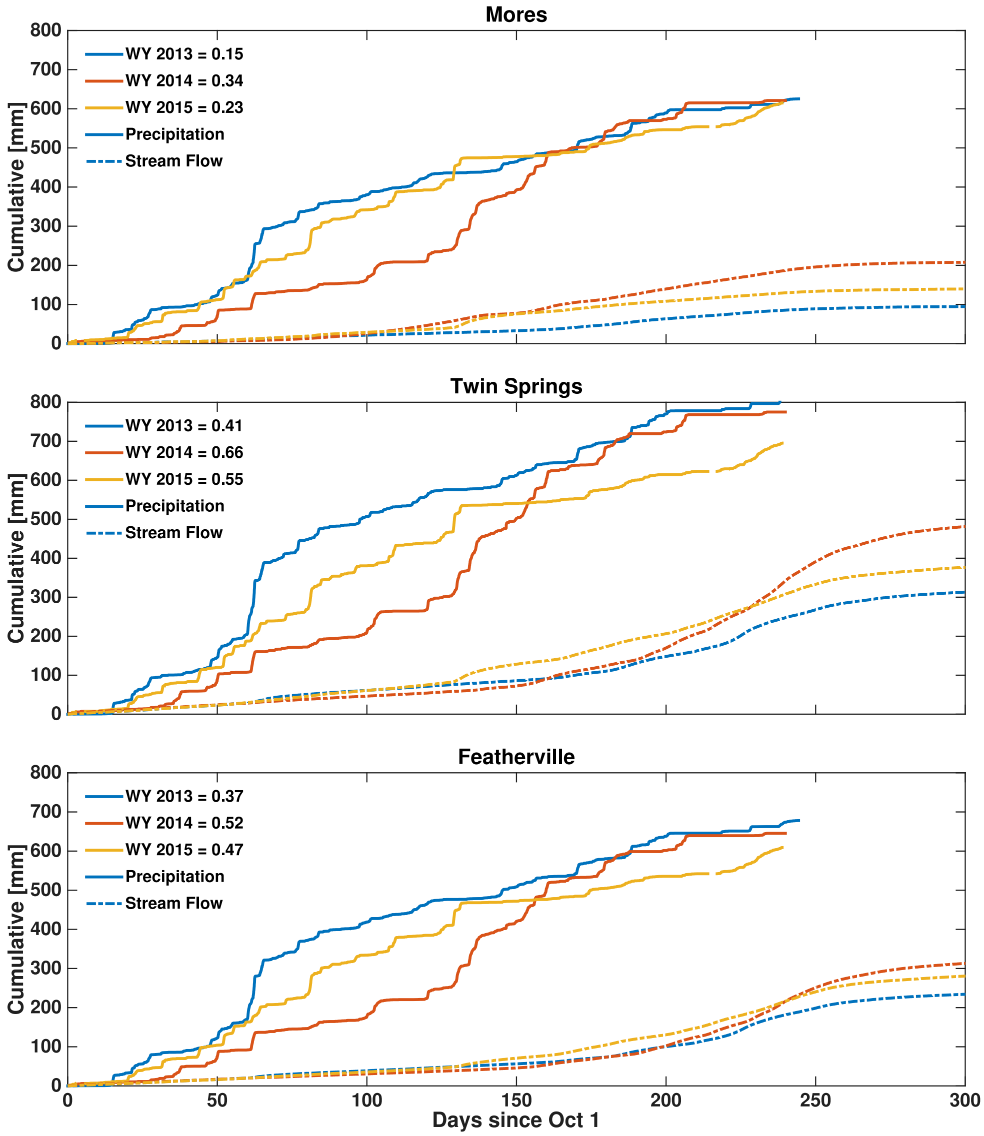

Figure 8. Comparing distributed precipitation to measured streamflow for Boise River basin subbasins. Yearly runoff ratios are in the legend.

SWE at a Point

Validating a spatially distributed model is difficult due to the lack of spatially distributed SWE measurements. SNOTEL locations offer point measurements of SWE in sheltered areas and SWE information about non-sheltered areas currently does not exist. Verification was performed comparing model results at eight SNOTEL locations. Two of the SNOTEL sites did not have adequate SWE measurements for two out of the three years. When comparing a point measurement at a SWE pillow (pillow area of 7 m^2) to the 100 m^2 model grid cell, one must take into account the differences in scale as well as the potential differences between the flat measurement site and the topographic model grid.

The eight SNOTEL locations used in the comparison are shown in Figure 9. Included in each plot are SWE data from all model grid cells within a 300 m by 300 m area surrounding the SNOTEL pixel location. For WY 2013 to WY 2015, the modeled SWE was slightly underestimated but follows the general trend of the snowpack. Melt out matched well with the SNOTEL network with WY 2014 melt out estimated slightly earlier for most stations.

The 300 m by 300 m grid around the pixel demonstrates how this high-resolution model handles variable topography and how the topography can effect snow accumulation and melt. At locations where nearby topographic positions and vegetation cover is similar, there is little variation in the model outputs (e.g., Jackson and Mores). At other sites, the local terrain and canopy cover is more complex and there is greater variation in SWE. At the Vienna site, there is also evidence of a modeling artifact produced by the combination of scales used to derive the forcing data. The Vienna site is located near the edge of one of the 4 km PRISM precipitation cells. The SWE values go from following the measured SWE well, to values close to zero due to the edge affect between two PRISM grid cells.

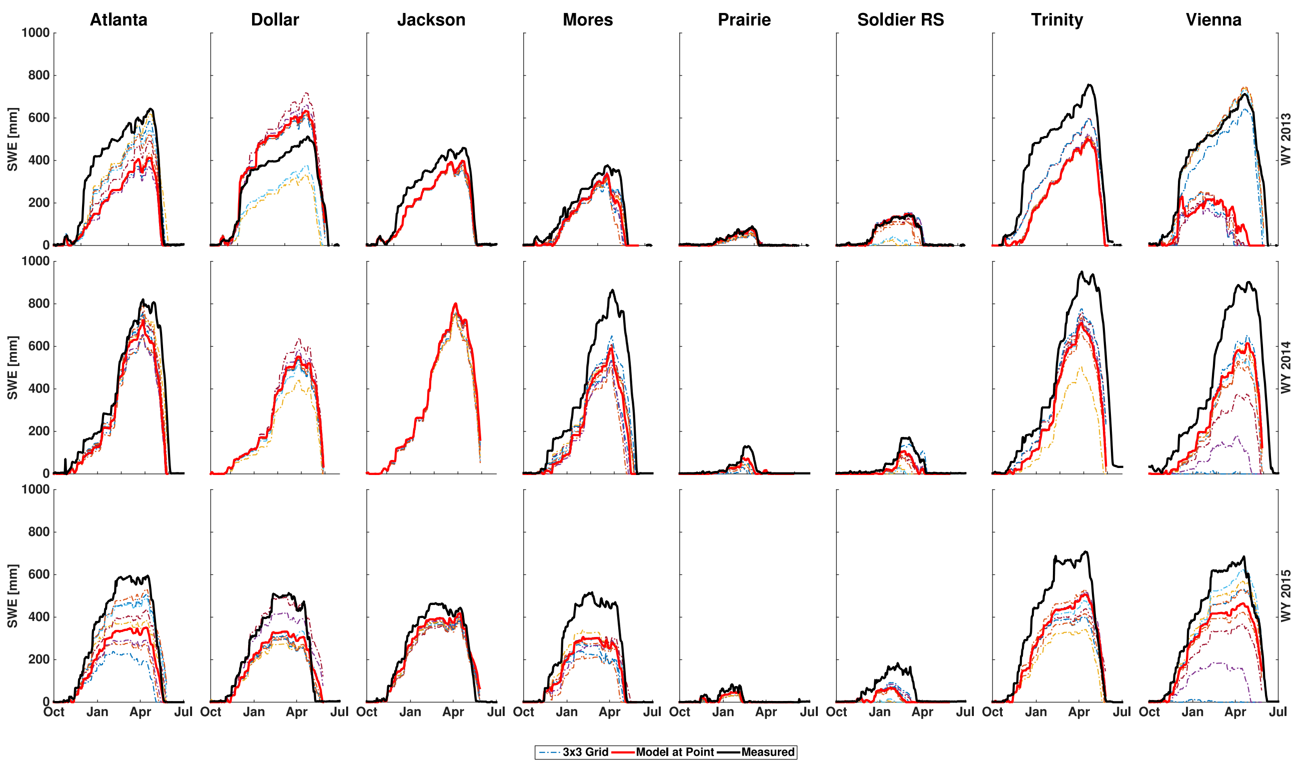

Figure 9. Modeled SWE versus measured SWE at 8 SNOTEL locations between WY 2013 and WY 2015.

Streamflow

The *iSnobal* – DHSVM coupling was calibrated to WY 2014, which had near normal snowpack and runoff. The calibration included setting parameters for three soil layers and roughness coefficients for overland and in-streamflow. Some of the soil properties required are porosity, pore size distribution, vertical and lateral hydraulic conductivity, field capacity, rooting depth, and bubbling pressures. The properties are set for each of the three soil layers at every point on the 100 m grid. A full parameter list for DHSVM is described in Wigmosta et al. (1994). Du et al. (2014) performed a sensitivity analysis with DHSVM and found that stream response was most sensitive to the soil porosity, hydraulic conductivity, and field capacity. Soil properties in this application were guided by the readily available NASA/NLDAS and NRCS/SSTATSGO datasets. These data sources, however, are low resolution depictions of attributes that are difficult to quantify and exhibit a high degree of spatial variability. Further calibration was required to best match the timing and volume of simulated and observed streamflows.

Three stream gauges exist in the Boise River basin, one for each of the subbasins: Featherville, Mores, and Twin Springs (Figure 1). The routing model was calibrated independently for each subbasin. The modeled results using SWI from *iSnobal* match some of the peaks and volumes of the measured streamflow (Figure 10). In Featherville, the volume and timing of the peak streamflow was captured, as well as the decline in flow during spring runoff. In contrast, the model predicted a Mores and Twin Springs melt event at the end of April that put a large amount of water into the system. However, this event did not occur, potentially due to parameter estimation.

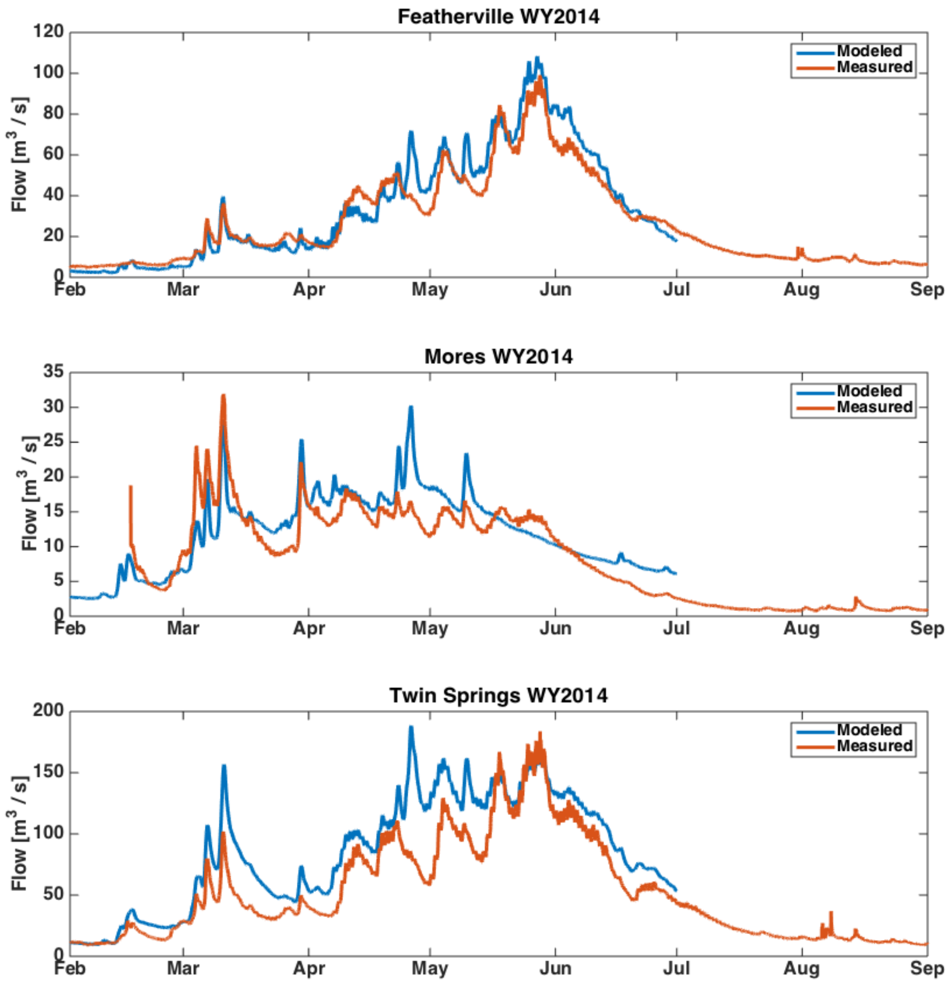

Figure 10. Measured versus modeled streamflow for coupled *iSnobal* and DHSVM.

DISCUSSION AND CONCLUSIONS

Real Time Modeling

For each of the 3 years that *iSnobal* was run over the Boise River basin, meaningful results about the snowpack state that are of significant potential benefit to Reclamation water managers. USDA-ARS provided Reclamation water managers with weekly snowpack SWE and cold content maps to inform where and how much snow is in the basin, the likelihood of snow melt, and the volume and location of where SWI was delivered to the basin since the last report.

In the final year, the coupling of three physically based models (WRF, *iSnobal*, DSHVM) was used to demonstrate the potential to use output from a short-term weather forecast (WRF), force a snow model (*iSnobal*), and produce streamflow (DHSVM). The results provided water managers with a 3-day streamflow forecast. Further work has been done to improve the methods for downscaling the WRF outputs based on terrain parameters. Havens et al., (In Prep) have successfully downscaled WRF outputs to force *iSnobal* for WY 2009 over the Boise River basin with ongoing work to improve the downscaling methods in order for them to be applied to real time WRF forecasts.

Weekly reports containing the *iSnobal* results were distributed to area water managers. The report contained information about the SWE distribution, estimated volume of water available, and changes from the past week. These reports provided water mangers another tool to aid in decision making and provided an independent check on the typical weather, snow, and forecast products integrated into the water manager's workflow. The weekly snow updates allowed Reclamation water managers to qualitatively compare their understanding of current conditions and whether or not they supported the water supply forecast trends. The *iSnobal* model estimates showed if they were vulnerable to over or under prediction due to the snow distribution or other possible assumptions.

In the future, operational routines for many snow dominated or snow-to-rain transitional basins would benefit from integrating physically-based snow models. These models are more robust to climate extremes and climate change, and provide spatial information not otherwise available from operational snow models such as SNOW-17 and SNODAS. Distributed SWE and liquid water volume (SWI) at the soil surface gained from *iSnobal* over the last 3 years have already aided water managers tasked with managing seasonal water supplies and runoff forecasting. The importance of these modeling tools will only increase as climate warming in the region continues. The distributed snow information will also be useful during the final reservoir fill period, which typically occurs during the last weeks of the snow runoff period. Final fills typically occur when the only remaining snow is at the highest elevations – well above most SNOTEL sites and the remaining snow available for melt is a relatively unknown. Historically, this has been an issue only late in the snow season, but as the climate warms, SNOTEL stations are melting out earlier, and are less representative of the snow cover volume and extent. The information will provide Reclamation water managers an additional tool to help mitigate the risk during the final fill period.

Snowpack Validation

Looking back at WY 2013 to WY 2015, the modeled SWE matched well with SNOTEL locations. Variability around the SNOTEL locations could be attributed to changes in topography, which affects the mass and energy balance. Variability can also be attributed to the precipitation phase, which relies on the forcing distribution techniques for air temperature and precipitation. Whether rain or snow, phase plays an important role in the physical process that modulate the snowpack. These situations occur often in the rain-snow transition zones that are key inputs to many Reclamation reservoirs. New methods are being investigated at USDA-ARS to further improve the distribution of air temperature and precipitation that will lead to more robust estimates of precipitation phase.

Streamflow Validation

The coupled *iSnobal*-DHSVM model was calibrated for the Boise River basin in WY 2014. Results showed agreement in the Featherville basin for peak runoff and timing but captured a melt event that did not occur in the other two subbasins. This shows that further calibration on multiple years is needed. Typically, DHSVM model parameters are constrained with multiple years of streamflow data, as hundreds of distributed parameters must be calibrated to three measurements of streamflow. Detailed, multi-year calibration of hydrologic model parameters in the Boise River basin was outside the scope of this project but will be addressed in S&T Project 8106 with USDA-ARS.

With the number of parameters required for DHSVM, we feel that DHSVM is probably too complicated for operational application. The calibration procedure will adjust DHSVM model parameters until measured and modeled streamflow are roughly matched, but it is not clear which parameters will need to be adjusted, and how that adjustment varies across the basin. This leads ARS to look at coupling *iSnobal* to simpler hydrologic models like the Precipitation Runoff Modeling System (PRMS) developed by the USGS (Markstorm et al. 2015). PRMS uses hydrologic response units to reduce the number of spatial units across the basin. The limitation of "off the shelf" PRMS is the snow model, which is a modified temperature index approach. If we can replace the snow model with *iSnobal*, we believe that we will have a robust model platform for forecasting from snow-dominated and affected mountain basins across the west.

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APPENDIX A – USDA AGRICULTURAL RESEARCH SERVICE SNOWPACK SUMMARY

Snowpack Summary
April 9 to April 16, 2015

USDA Agricultural Research Service, Boise ID

1 Summary

The past week saw a storm that brought more snow to higher elevations with an average of about 1 inch of snow water equivalent (SWE) above 7,770 ft. The new snow and colder temperatures have lead to a minimal loss of water (about 16.3 KAF) this week. The upper elevation snowpack has an average of about 15 inches of SWE above 8,000 ft with decreasing SWE at lower elevations.

2 Weather

On Saturday April 11th, a large storm came through the Boise River Basin (BRB). Total precipitation amounts ranged from 0.3 to 0.9 inches of water, favoring the Mores Creek area and northern parts of BRB. The storm temperature's hovered around freezing for most of the stations, with higher elevation stations above about 7,000 ft seeing mainly snow. The storm increased SWE at the higher elevation ranging between 0.3 and 0.9 inches.

Station	Elevation [ft]	Min Temp [F]	Max Temp [F]	Precip [in]	SWE [in]
Mores Creek	6100	22	59	0.8	-0.4
Jackson Peak	7070	18	55	0.9	0.6
Atlanta Summit	7580	18	53	0.5	0.4
Vienna Mine	8950	13	48	0.4	0.9
Dollarhide Summit	8400	18	48	0.3	-
Trinity Mountain	7770	17	56	0.5	0.3

Table 1: Weather summary form select SNOTEL stations over the past week.

3 Current Model Results

The current model results were updated April 16, 2015.

- The distribution of SWE (Figure 1) shows the majority of the water is at higher elevations, with lower to mid-elevations having a minimal snowpack.
- The cold content (energy required to produce melt) shows that the majority of the snowpack is cold and not capable of producing melt without an increase in energy input (Figure 1 and 3).
- The distribution of SWE as a function of elevation (Figure 2) shows large range in SWE for a given elevation band, with a decrease in SWE around 8,000 feet.
- The water available for potential melt is estimated at 43 KAF or 10% for the BRB (Figure 3). This is due to the colder weather experienced over the past couple days.
- Upper Twin Springs Basin results are under-predicating SWE due to the lack of precipitation measurements in that location.

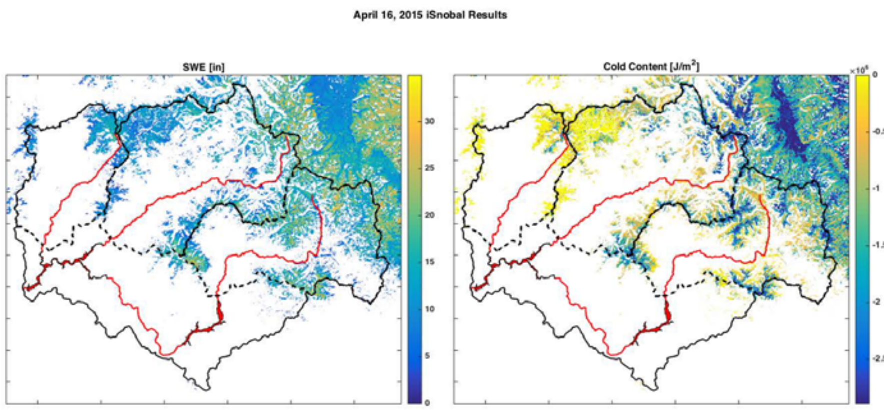

Figure 1: Current modeled SWE and cold content (yellow close to melting).

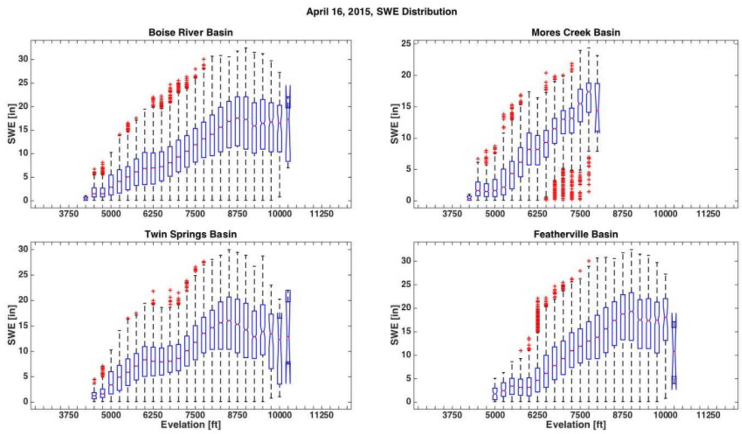

Figure 2: Current modeled SWE range as a function of elevation.

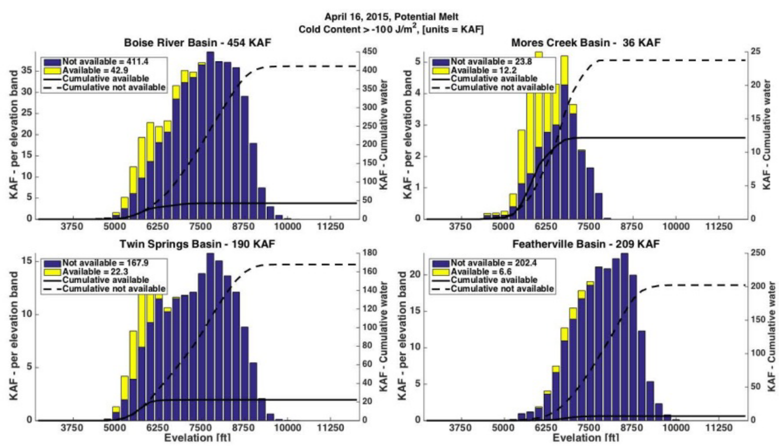

Figure 3: Potential water available or not available for melt as a function of elevation.

4 Weekly Changes

Comparing the changes between the last model run on April 9, 2015 and the current model run on April 16, 2015.

- The storm this week added up to 2 inches of SWE to the higher elevations (Figure 4).
- The upper elevations were favored with an average increase of 1 inch of SWE above 7,770 ft (Figure 5).
- Lower to mid elevations showed an average decrease in SWE of 1 inch below 6,500 ft (Figure 5).
- The change in water volume of BRB was estimated at -16.3 KAF with the majority of loss coming from below 7,500 ft. Higher elevations showed an increase in water volume in the Twin Springs and Featherville Basins (Figure 6).

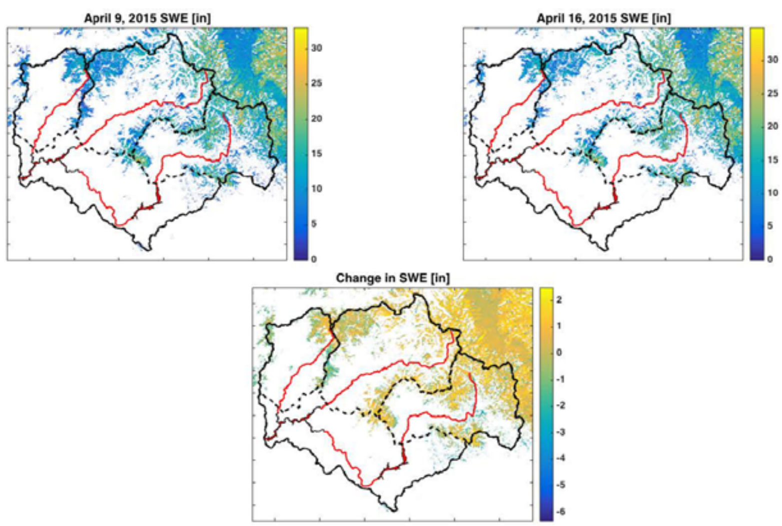

Figure 4: Current modeled SWE compared with last week's model results.

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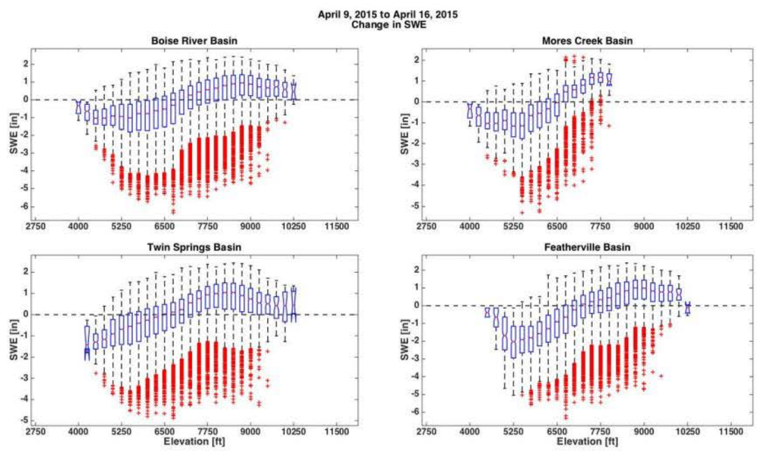

Figure 5: Current modeled SWE change since last week's model results as a function of elevation.

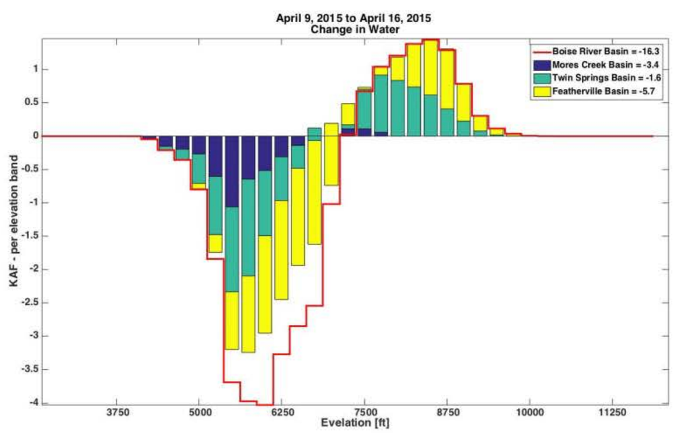

Figure 6: Change in water volume since last week's model results as a function of elevation.

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