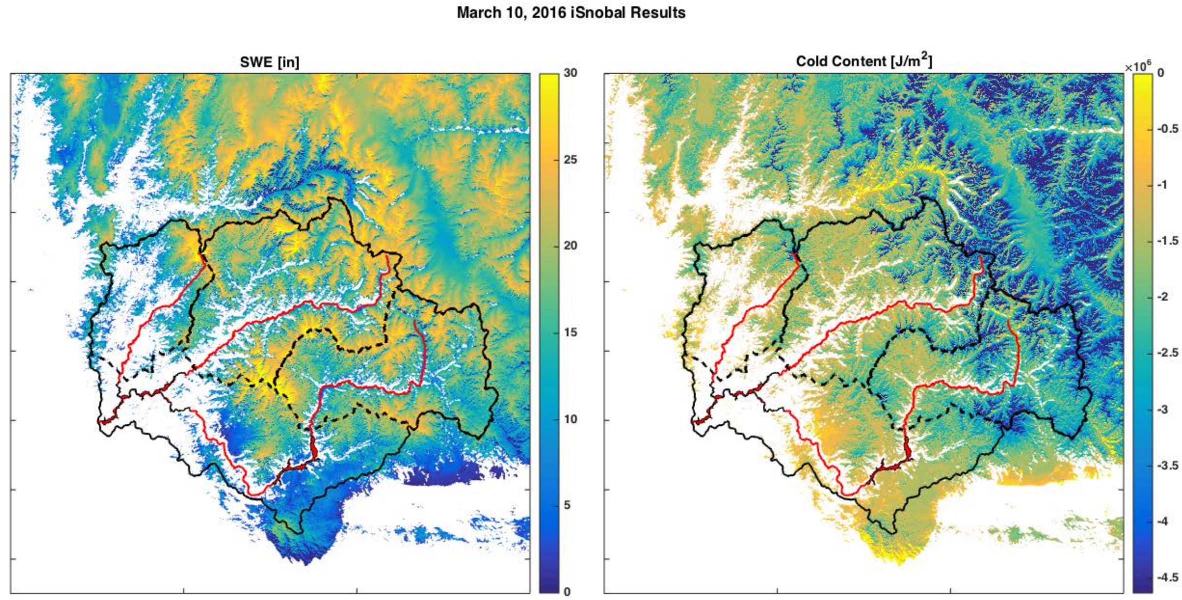
RECLAMATION
Managing Water in the West

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-2016-2157-1



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

September 2016

U.S. DEPARTMENT OF THE INTERIOR

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Current operational snowmelt models are derived from statistical relationships between historic point measurements of SWE, and rarely contain detailed physics-based model representations. The statistical models have been shown to be unreliable in non-normal conditions that have not been observed in the past or due to changing climatic conditions. In contrast, physically based, distributed models represent the actual physical processes and are as accurate as the forcing information, making them more robust to non-normal conditions. They have the potential to improve reservoir management decisions by providing distributed snowpack properties that are resilient to climate change. This project extended a previous project (S&T 2264) and focused on applying the physically based, distributed snow model iSnobal in an operational setting for water year 2016. Forcing data for iSnobal was derived from a short term weather forecast to provide a 3-day snowpack forecast in real time. The snowpack results, such as spatially distributed snow water equivalent (SWE), susceptibility to melt, the volume of liquid water delivered to the soil (snow melt or rain), and the 3-day forecast were provided on a weekly basis to local area water managers. The results show great agreement between model results and SNOTEL measurement locations, building confidence that the results can be used and trusted in an operational setting.

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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 ______________________________ Date Reviewed: 9/20/16
(Signature)

Executive Summary

Current operational snowmelt models are derived from statistical relationships between historic point measurements of snow water equivalent (SWE) and rarely contain a detailed physics-based model representation. The statistical models have been shown to be unreliable in non-normal conditions that have not been observed in the past, or due to changing climatic conditions. In contrast, physically-based, distributed models represent the actual physical processes, and are as accurate as the forcing information, making them more robust to non-normal conditions. They have the potential to improve reservoir management decisions by providing distributed snowpack properties that are more resilient to climate change than simpler models, i.e., temperature index snowmelt models. This project extended a previous project (S&T 2264) and focused on applying the physically-based, distributed snow model *iSnobal* in an operational setting for water year (WY) 2016. Forcing data for *iSnobal* was derived from a short-term weather forecast to provide a 3-day snowpack forecast in real time. The snowpack results, such as spatially distributed SWE, susceptibility to melt, the volume of liquid water delivered to the soil (snow water input [SWI], snow melt or rain on bare ground), and the 3-day forecast were provided on a weekly basis to local area water managers. The results show great agreement between model results and SNOTEL measurement locations, building confidence that the results can be used and trusted in an operational setting.

Acronyms and Abbreviations

BRB	Boise River Basin
BSU	Boise State University
DHSVM	Distributed Hydrology Soil Vegetation Model
ET	evapotranspiration
GCMs	Global Climate Models
km	kilometer
km^2	square-kilometers
LEAF	Lab for Ecohydrology and Alternative Futuring
m	meter
mm	millimeters
NRCS	Natural Resources Conservation Service
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
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 (often seasonal volume runoff forecasts) are derived from statistical relationships, largely based on a historic trends, and calibrations to a combination of point observations of SWE, precipitation, runoff metrics, and occasionally satellite observations of snow-covered-area. These models rarely contain detailed physics-based representations of the mass and energy fluxes. It has been shown that such models become unreliable when non-normal conditions are encountered.

More complex physically-based, distributed models require minimal calibration and can be forced with current and future conditions with more confidence than statistically-based approaches, especially in a changing climate. The physical basis means that all mass and energy fluxes that affect the snowcover are numerically estimated based on the governing physics. These models are more 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.

Up until now the criticism of more complex physically-based models has been that they required large computational resources, and that simpler, parameterized models were more appropriate for operational use. A lack of driving data (i.e., mountain weather observations) for physically-based modeling has also been seen as an impediment to more complex solutions. Today however, computational capabilities have multiplied, efficient techniques for distributing limited observations have been developed, and gridded weather forecasts are readily available.

Project Goals

The project goals were as follows:

1. Continuation of the real time modeling using available data from meteorological stations and from a short-term gridded weather forecast.

2. Improvement of the downscaling methods used to take gridded weather forecasts (3 kilometers [km]) and apply them to the snow modeling domain (100 meter).

3. Provide weekly SWE, cold content, SWI, and interpretive summaries for the past week, in addition to a short-term forecast.

Products

For water year (WY) 2016, the U.S. Department of Agriculture – Agricultural Research Service (USDA-ARS) provided weekly updates on the snowpack state and the short-term 3-day forecast from March 1, 2016 to May 26, 2016. The weekly product was delivered to the Bureau of Reclamation (Reclamation), other members of the Idaho Water Supply Committee, and other interested parties.

STUDY AREA

Reclamation operates three large reservoirs in the Boise River Basin (BRB), defined as the watershed above Lucky Peak Dam, which drains an area encompassing roughly 7,000 square-kilometers (km^2). Reclamation water managers operate the three reservoirs, Anderson Ranch, Arrowrock, and Lucky Peak as a system to balance flood control, environmental needs, irrigation water supply, and recreational uses. As a snow-dominated watershed, water managers require accurate information about the seasonal snow pack, the volume of water produced by snowmelt, and when potential melt may occur due to rain-on-snow events.

For WY 2016, the modeling domain was expanded in order to include more meteorological stations that surround the BRB, and to capture a larger range in elevations. The domain size was 1500 by 1500 pixels with 100 meter spacing (Figure 1). A total of 50 stations were used, a large increase from 18 in the previous project (Havens et al. 2015), to determine if increasing the number of stations not only improved model results, but if the data could be quality controlled in real time. However, not all were used at the same time due to either data quality issues or missing data. The stations were from the Natural Resource Conservation Service (NRCS) SNOTEL network, Reclamation, Bureau of Land Management, National Weather Service, Idaho Transportation Department, and the Sawtooth Avalanche Center. The stations measured a combination of variables required for the models runs, like precipitation, air temperature, relative humidity, wind speed and direction, and incoming solar radiation.

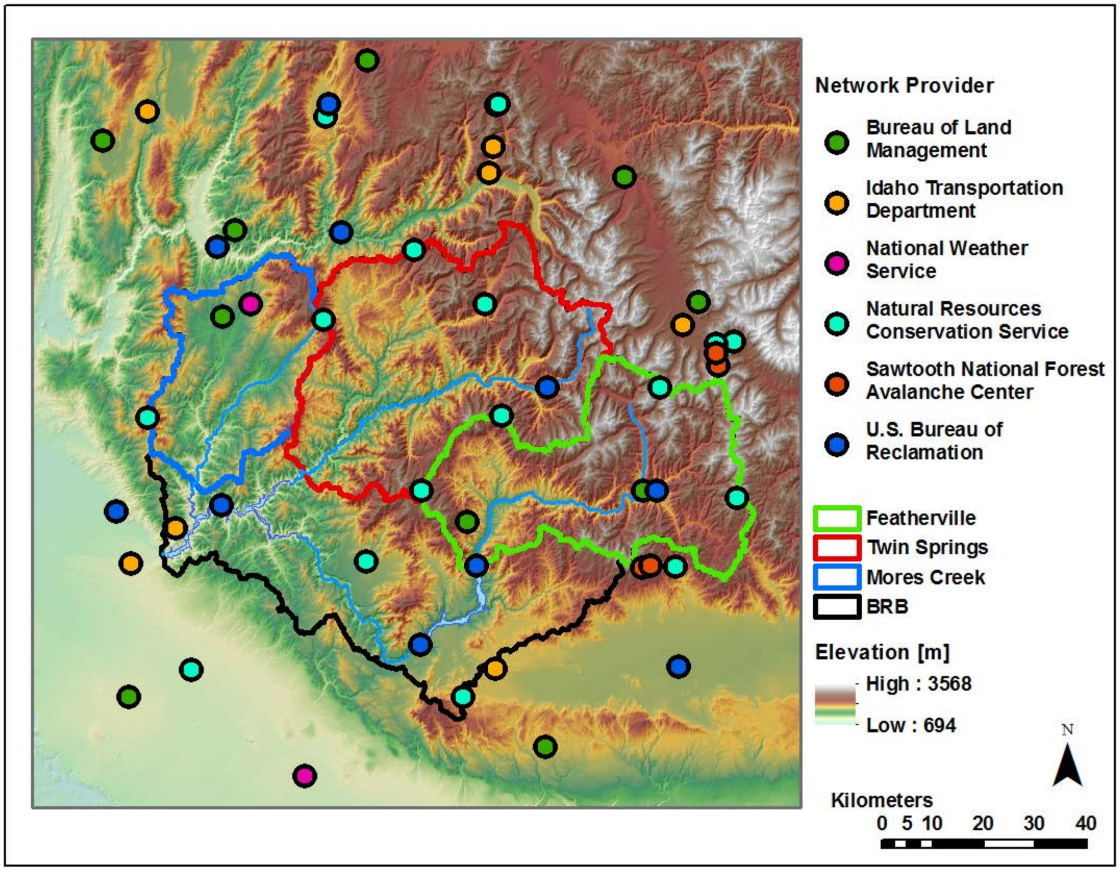

Figure 1. BRB with the network provider for the meteorological stations used in WY 2016. Subbasins Mores Creek, Twin Springs, and Featherville are outlined (left to right).

MODEL DESCRIPTIONS

iSnobal

iSnobal is a physically-based distributed snowmelt model that solves the energy and water balance in 1-D at each pixel over a DEM grid (Marks et al. 1999). The snowpack is represented as two layers, with the surface layer transferring energy with the atmosphere and the lower layer transferring energy between the surface layer and the soil (Figure 2). The forcing data required for *iSnobal* are raster datasets over the DEM and include incoming thermal (long-wave) radiation, air temperature, vapor pressure, wind speed, solar radiation, precipitation mass, precipitation phase (rain or snow or mixed), precipitation density, and precipitation temperature. Given the forcing inputs, *iSnobal* calculates the energy and water balance at each grid cell, solving for the snowpack temperature, density, mass, liquid water content, and cold content (energy required to bring the snowpack to 0^o Celsius). Melt occurs when the snow temperature is at 0^o Celsius and has a cold content of zero.

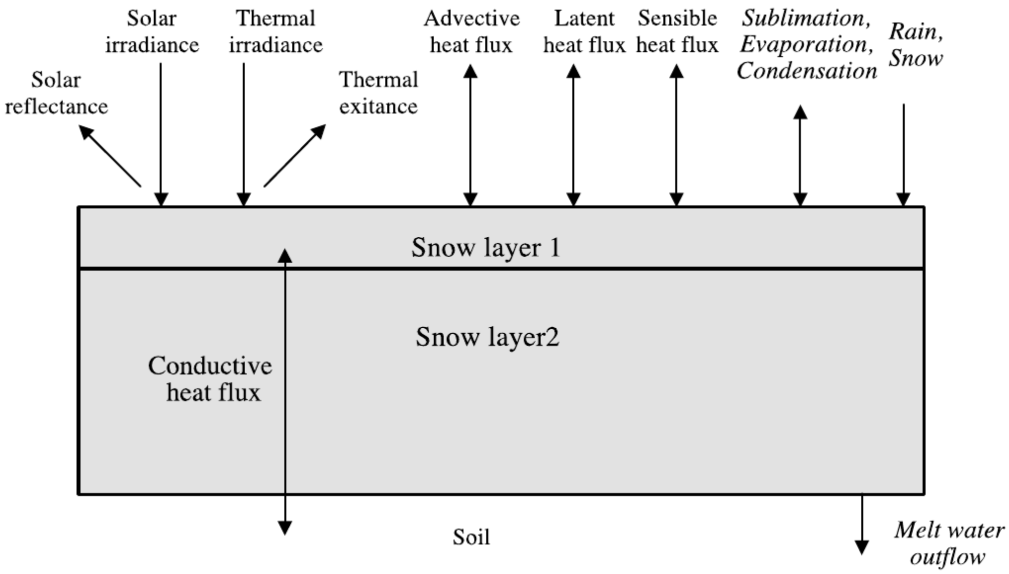

Figure 2. ***iSnobal*** **snowpack diagram for the energy and mass fluxes (italics) calculated (from Garen and Marks (2005).**

Weather Research and Forecasting

The Weather Research and Forecasting (WRF) model is a numerical weather prediction system that is used to dynamically downscale coarser Global Climate Models (GCMs) (Figure 3). WRF is typically run at resolutions down to 1 km past atmospheric simulations, where larger GCM have used data assimilation with available measurements to most accurately represent the climate at that time. Real time modeling ran at scales between 2 and 3 km in order to keep computational costs reasonable and to provide results in a timely manner. Atmospheric and surface conditions are generated by WRF using initial conditions from the GCM's. WRF has been used extensively by both research and operational organizations, and is under constant development. WRF offers operational forecasting a flexible and computationally-efficient platform, while providing recent advances in physics, numeric, and data assimilation contributed by developers across the very broad research community.

Boise State University (BSU) Lab for Ecohydrology and Alternative Futuring (LEAF) provided the short-term 3-day forecast from WRF at 3 km resolution (S&T 9682). The surface outputs for temperature, relative humidity, precipitation, wind speed, and long wave radiation were downscaled to the 100 m *iSnobal* domain, detailed below. The modeled solar radiation was corrected using the average cloud cover over all modeled atmospheric layers. Deriving forcing data for *iSnobal* from WRF provided operational water managers a 3-day forecast for change in SWE and snowmelt expected.

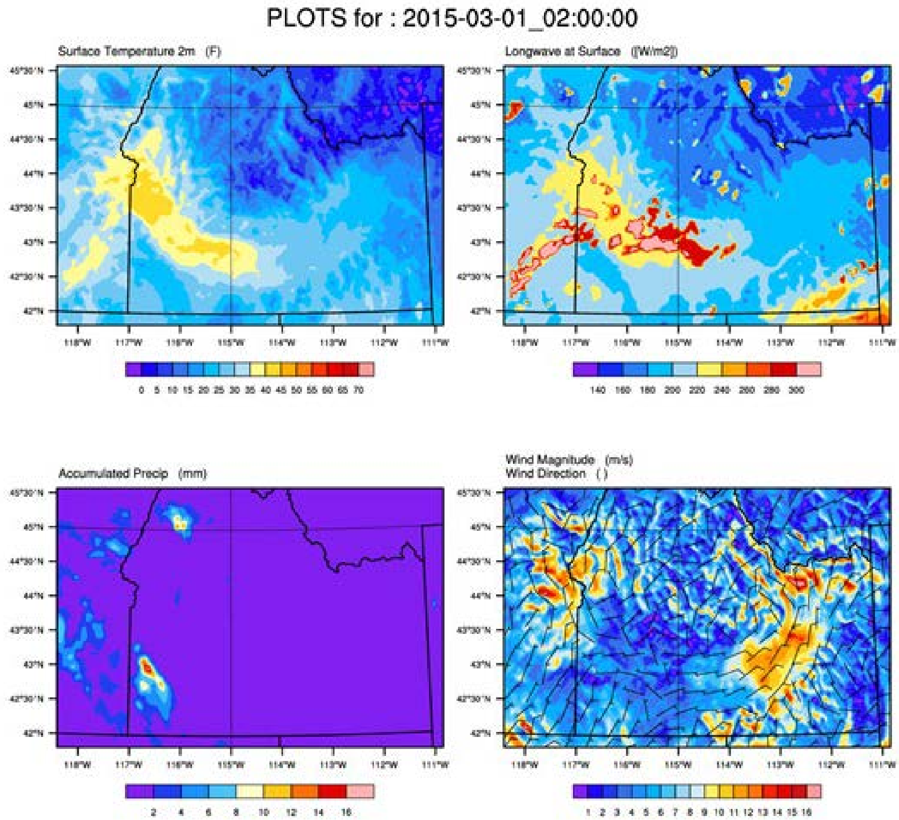

Figure 3. Example WRF output for the 2 m surface temperature, incoming longwave radiation at the surface, accumulated precipitation, wind speed and direction.

REAL TIME MODELING: WATER YEAR 2016

The past project (S&T 2254) provided a great foundation that allowed ARS to test and deploy different techniques for running *iSnobal* in real time. For example, ARS developed more efficient methods for developing forcing data from station measurements and WRF for the real-time application of *iSnobal*. Changes also were included in the weekly report summary with new figures and provided the short-term 3-day forecast.

Forcing Data Development and Model Runs

Based on previous projects, ARS developed a new framework, Spatial Modeling for Resources Framework (SMRF), which simplifies the development of forcing data. The goal of SMRF was to increase the efficiency of modeling large basins in real time, allow for more meteorological stations to be incorporated, to be modular in nature to allow new methods or variables to be easily added, and to increase the flexibility with new distribution methods. SMRF was applied in real time for WY 2016 in both the BRB, and the Tuolumne River Basin in California to provide model results to the Airborne Snow Observatory (Painter et al. 2016).

SMRF is an open source project developed in Python, with computational tasks implemented in C. The source code is available on the ARS Boise code repository, complete with online documentation.

All the input variables required to run *iSnobal*, which are air temperature, vapor pressure, precipitation, wind speed, incoming thermal radiation, and solar radiation are distributed with SMRF. Each variable can utilize a different number of stations and distribution methods. The distribution methods currently implemented are inverse distance weighting, detrended kriging (Garen, Johnson, and Hanson 1994; Garen and Marks 2005), and gridded interpolation for gridded datasets (i.e., WRF). All the data is distributed at each time step before continuing to ensure that if an error occurs, all the dependent variables can be easily updated. The distributed data was output to files for viewing and running *iSnobal*.

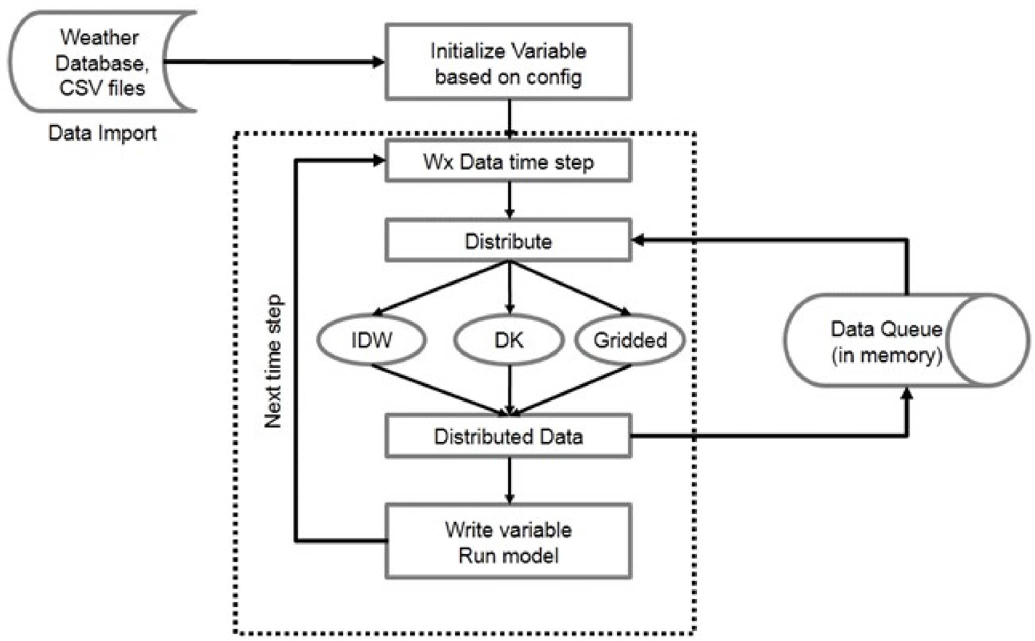

Figure 4. Flowchart for SMRF. Data is imported from CSV files or MySQL database. Each variable follows the same steps with a data queue for multi-threaded applications. See the online documentation for more in-depth information.

During the weekly updates, the station measurements were quality controlled with simple gap filling, smoothing, and precipitation correction. The meteorological measurements were distributed with SMRF using inverse distance weighting and detrended kriging. The number of stations used for real time modeling was significantly increased from the last 3 years, from 18 to 50, with significant stations added around the perimeter of the BRB. The addition of more stations helped to interpolate around the edges of the basins to provide more robust estimates of the spatial fields, and filled in spatial data gaps where information was lacking previously. With the distributed data from SMRF, the inputs were passed to iSnobal to restart the model run for the week. The week's modeling ended at 06:00 UTC (00:00 MST) to align with the WRF forecast start time.

The short-term 3-day forecast was downscaled to the modeling DEM using gridded linear interpolation within SMRF. The methods for downscaling were vastly improved since S&T 2254 and are based on the work by (Havens et al., In Prep). The methods assume that each WRF grid cell is a station measurement with an X, Y, and elevation. Then similar techniques can be applied, for example, detrending the data with elevation prior to distributing across the model domain. The distribution used gridded linear interpolation due to the increased number of grid points (greater than 2000 grid cell within BRB). The WRF model started at 06:00 UTC (00:00 MST) and *iSnobal* was initialized using the weekly run up to that point. This ensured that there was a smooth transition between the weekly run and the 3-day forecast.

The typical weekly workflow took, on average, less than 4 hours to complete the following steps:

1. Quality control meteorological data for 50 stations (air temperature, relative humidity, wind speed, wind direction, solar radiation, and precipitation).
2. Distribute meteorological data with SMRF and run *iSnobal.*
3. Download WRF forecast.
4. Distribute WRF forecast with SMRF and run *iSnobal* after weekly run was complete.
5. Prepare weekly report.

Weekly Report Summary

The weekly report summary was mostly unchanged when supplying information about the current conditions. The information provided was a summary of the past week's weather, a map of SWE, map of cold content, SWE by elevation band, potential melt and water volume by elevation band. New to the current conditions was a validation image, showing the modeled SWE compared with the measured SWE at select SNOTEL locations. This provided some information to users as to whether or not iSnobal was producing reasonable results.

The weekly report provided maps of current SWE, change in SWE from the previous week, snow water input (SWI, snow melt from the bottom of the snowpack or rain on soil); and several plots that provided weekly change in SWE by elevation band, change in water volume by elevation band, and SWI by elevation band. SWI was included to provide water managers an estimate of the volume of water that has left the snow pack or entered the system as rain, and is available to the rest of the hydrologic system over the past week. This value provides an estimated upper limit to the volume of water that has entered the hydrologic system.

The newest section was the short-term forecast, which displayed the changes projected over the 3-day forecast period for SWE by elevation band, change in water volume by elevation band, and SWE by elevation band. These figures provided information on new precipitation that was expected or melt that may occur from rain or high temperatures. SWI provided useful information on the potential water volume that could enter the hydrologic system, given that the forecast was reasonable.

See Appendix A – USDA Agricultural Research Service Snowpack Summary for the report format that was distributed to Reclamation, local area water managers, and other interested parties.

MODELING RESULTS

SWE Validation

Validation of a high-resolution model at a large spatial scale is difficult, due to the limited number of reliable remote sensing platforms that have the ability to quantify the snowpack. Therefore, we are left with comparison to existing SNOTEL locations in and around the BRB. For this study, 12 SNOTEL locations were compared with model results and were presented in the weekly report to track the model progress throughout the snowmelt season (Figure 5). However, when comparing SNOTEL measurements to *iSnobal* results, two factors must be taken into account. First, there is a significant scale difference between a 7 m^2 pillow and the 10,000 m2 model pixel. There was also topography in the model pixels at the SNOTEL locations, making it different than the standard flat and sheltered SNOTEL site. Therefore, when comparing SNOTEL to *iSnobal* model results, some differences between measured and modeled can be attributed to the scale and topographic differences. Secondly, the model results at the SNOTEL locations are being driven with the forcing data from that measurement site and the validation then becomes that how well station measurements perform at forcing *iSnobal*. The spatial distribution of the forcing data will be a major source of uncertainty in the model simulations, but short of repeated spatial measurements, the uncertainties away from measurement locations are difficult to address.

To address the potential topographic differences, a 300-meter by 300-meter (9 total model pixels) area surrounding the SNOTEL location were included to characterize the spatial variability around the site. Taking these factors into account, the model results agree well with SNOTEL measurements for the peak SWE, snowpack depletion, and final melt out date. Even though there is some spread in some of the model results (i.e., Dollarhide Summit, or Banner Summit), there are always one or two pixels that follow the trend in SWE very well. Also of note. was Graham Guard Station and Prairie which did not have reliable precipitation measurements for most of the winter. However, the modeled SWE matches extremely well, indicating the precipitation distribution method was accurately capturing the trends in precipitation over those areas. These types of results build confidence not only in SMRF but the distribution methods used for all variables.

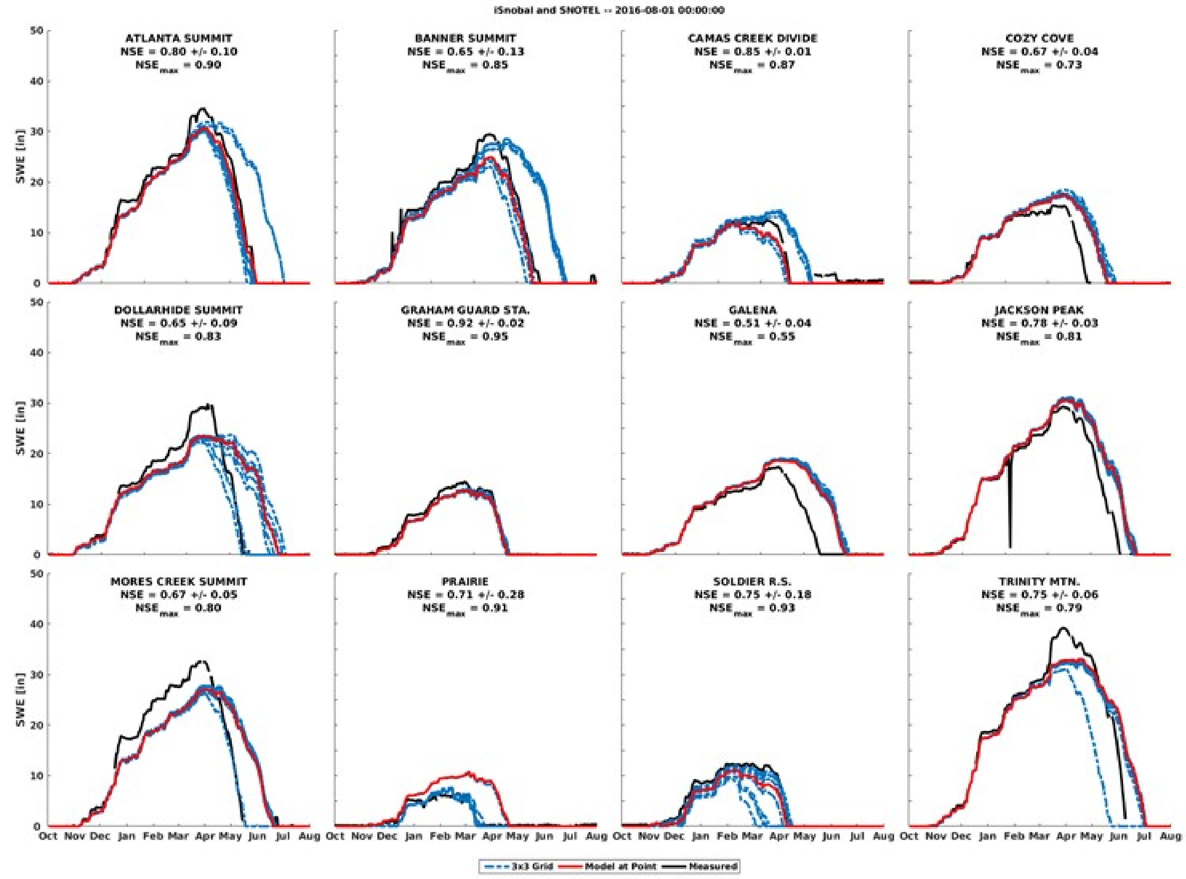

Figure 5. Comparison between 12 SNOTEL measurement locations (black line) and model results. Red line represents the pixel with the SNOTEL station and the blue dashed lines represent a 300-meter by 300-meter (9 total grid cells) around the measurement location. *iSnobal* performed well at most locations with differences in peak SWE and melt out due to the topographic or vegetation representation in the model.

Basin Water Volume

When running a spatially distributed model, it is important to ensure that enough precipitation is distributed to account for both streamflow and evapotranspiration (ET). Based on two of the major vegetation types in the BRB, ET estimates measured from eddy covariance towers are 300 mm yr-1 for sagebrush (Flerchinger et al. 2010) and between 400 to 800 mm yr-1 for ponderosa pine (Ha et al. 2015; Goulden et al. 2012). For the entire year, the precipitation, SWI, and measured streamflow were accumulated (Figure 6) for each subbasin. The difference between the precipitation and measured streamflow, normalized by the basin area, was 500 mm for Mores, 400 mm for Twin Springs, and 350 mm for Featherville. These values are within the range of measured ET, indicating that enough precipitation was distributed to account for ET and streamflow.

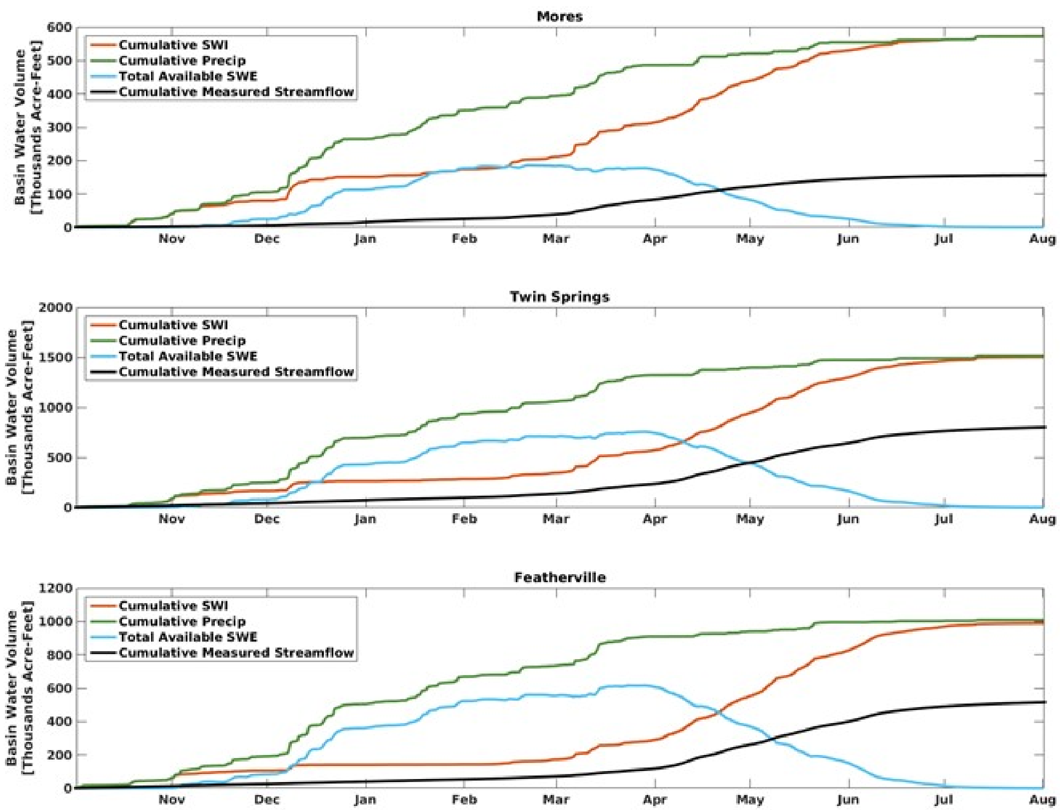

Figure 6. Comparing the basin water volume to modeled SWI and measured streamflow for each subbasin. Total subbasin water volume as SWE in blue, cumulative SWI in orange, and cumulative streamflow in black.

CONCLUSIONS AND FUTURE WORK

A new forcing data development framework was tested for WY 2016 using up to 50 stations to force *iSnobal*. SMRF provided an efficient method to distribute the forcing data quickly and easily, allowing time to perform other tasks that were not performed in the past, like snowpack validation in real time. This efficiency and validation provides modelers immediate feedback on performance of the point model by comparing results to SNOTEL measurements. At the end of the model runs on August 1, 2016, the measured SWE matched extremely well to model results with variance mainly due to topography or vegetation differences between the model and the SNOTEL location. The difference between SWI and streamflow can be explained by reasonable estimates of ET. The model results build confidence in using SMRF in an operational context and could provide water managers an easy to use tool for developing distributed forcing data for *iSnobal* or other hydrology models.

The 4-year project with Reclamation's Pacific Northwest Regional Office has been instrumental in the development of methods for applying physically-based models in real time. For the first time, a physically-based snow energy balance model was coupled to a weather forecasting model, providing new 3-day estimates of SWI and change in SWE. We will be continuing the progress made with another potential project with Reclamation's Mid-Pacific Regional Office, furthering the development for coupling *iSnobal* with a hydrologic model in the Upper San Joaquin. We also anticipate model efforts to continue in the BRB for a project with the NRCS, also furthering the coupling, real time methodologies, and developing forecasting tools based on physically based models.

The next major step to use iSnobal in an operational setting will be to perform multi-year studies to validate and improve the model over a wide range of seasonal conditions. We plan to run *iSnobal* over a 15-year time span (2001 to 2016) where we can then develop new forecasting tools, based on relationships between the distributed snowpack and measured streamflow. With the distributed snowpack information and the robustness of physically-based models to extreme climate events, the hope is to have new statistical water supply forecast relationships that are resilient to changing climate conditions and have the potential to lower the uncertainty in water supply forecasting.

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Parenthetical Reference	Bibliographic Citation
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APPENDIX A – USDA AGRICULTURAL RESEARCH SERVICE SNOWPACK SUMMARY

The WY 2016 distribution list was up to 32 people. The following agencies received the weekly report:

- Boise State University
- Bureau of Reclamation
- Idaho Department of Water Resources
- Idaho Power
- NASA Jet Propulsion Laboratory
- Northwest River Forecast Center
- NRCS Idaho
- NRCS National Water and Climate Center
- Pioneer Irrigation District
- San Francisco Public Utilities
- Sawtooth National Forest Avalanche Center
- State of Idaho Water District 63
- SWL Institute for Snow and Avalanche Research (Switzerland)
- USDA Agricultural Research Service
- USDA Forest Service
- Utah State University

Boise River Basin Snowpack Summary
March 7 to April 12, 2016

USDA Agricultural Research Service, Boise ID
U.S. Bureau of Reclamation, Boise ID

1 Summary

High temperatures have now reached the highest elevations in the Boise River Basin with minimal freezing night time temperatures. The model results indicate the majority of the snowpack has reached isothermal conditions during the day. This led to a decrease in water storage of 181 KAF and snow water input (SWI, water entering the hydrologic system) of 184 KAF. The 3-day forecast has a period of unsettled weather beginning this afternoon with the potential for some new snow in the higher elevations and rain at the lower elevations. The SWI forecast by April 15 is 151 KAF.

2 Weather

Warm day time temperatures and above freezing night time temperatures were observed up to the highest SNOTEL stations. No precipitation was recorded with SNOTEL locations loosing between 1 and 4 inches of SWE.

Station	Elevation [ft]	Min Temp [F]	Max Temp [F]	Precip [in]	SWE [in]
Mores Creek	6100	36	67	0	-4.0
Jackson Peak	7070	41	67	0	-2.0
Atlanta Summit	7580	39	66	0	-3.2
Vienna Mine	8950	34	62	0	-1.2
Dollarhide Summit	8400	39	56	0	-3.0
Trinity Mountain	7770	31	65	0	-2.1

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

3 Current Model Results

The current model results were updated April 12, 2016 at 00:00:00 local time.

- The distribution of SWE (Figure 1) shows significant coverage remaining at high elevations with lower elevations melting quickly.
- The cold content (energy required to produce melt) shows that the snowpack is not cooling at night due to the above freezing temperatures and will require much cooler temperatures to slow melt (Figure 1 and 3).
- The distribution of SWE as a function of elevation (Figure 2) shows an average of greater than 20 inches at higher elevations with SWE decreasing around 6,500 feet.
- The total water stored in the snowpack in estimated at **1,450 KAF** with water available for potential melt estimated at **1442 KAF** for the BRB during the day (Figure 3). The model results indicate that the majority of the BRB has reached isothermal conditions during the day and will produce melt.
- Validation of modeled SWE results show great agreement with SNOTEL (Figure 4) increasing our confidence in the modeled results. Validation shows a potential undercatch at some of the more exposed and windy SNOTEL location.

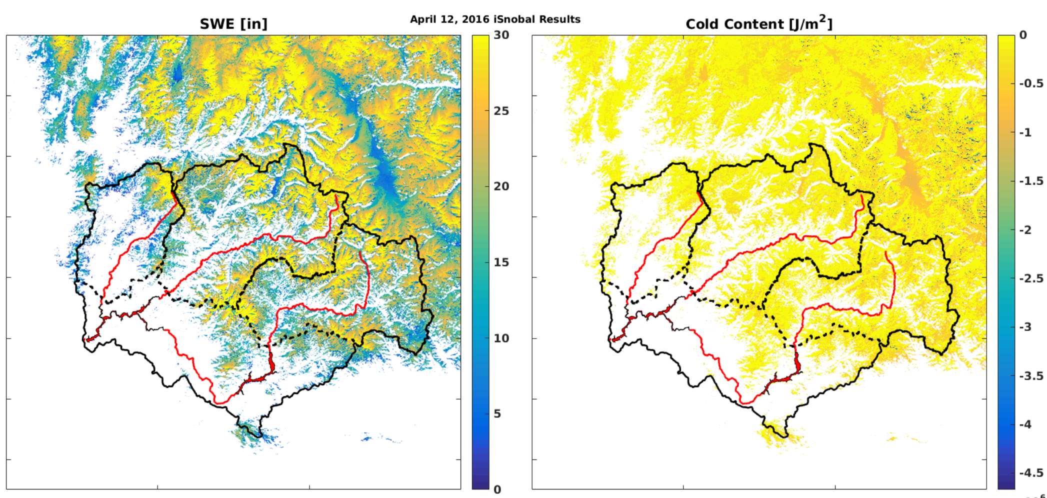

Figure 1: Current modeled Snow Water Equivalent (SWE) on the left and cold content on the right with yellow indicating that the snowpack is close to or already melting).

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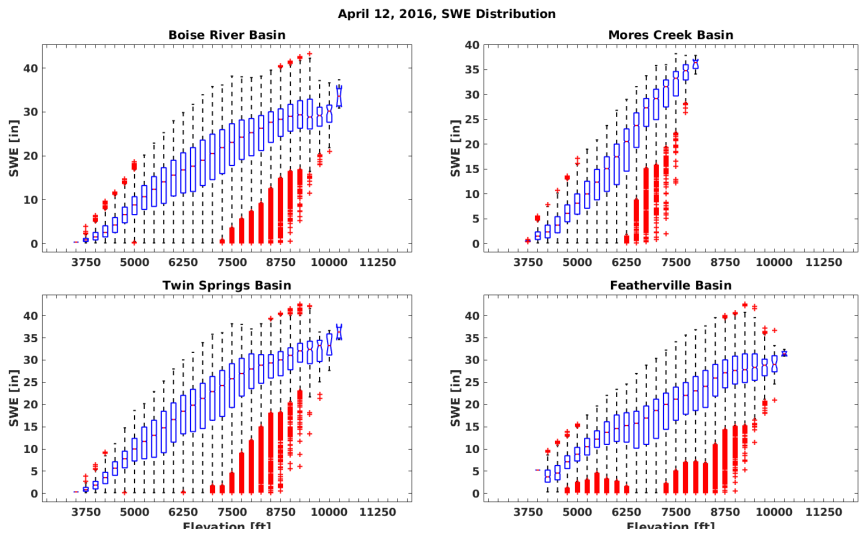

Figure 2: Current modeled SWE range as a function of elevation. Central mark is the median, edges of the box are 25th and 75th percentiles, the whiskers cover 99% of the data, with outliers in red.

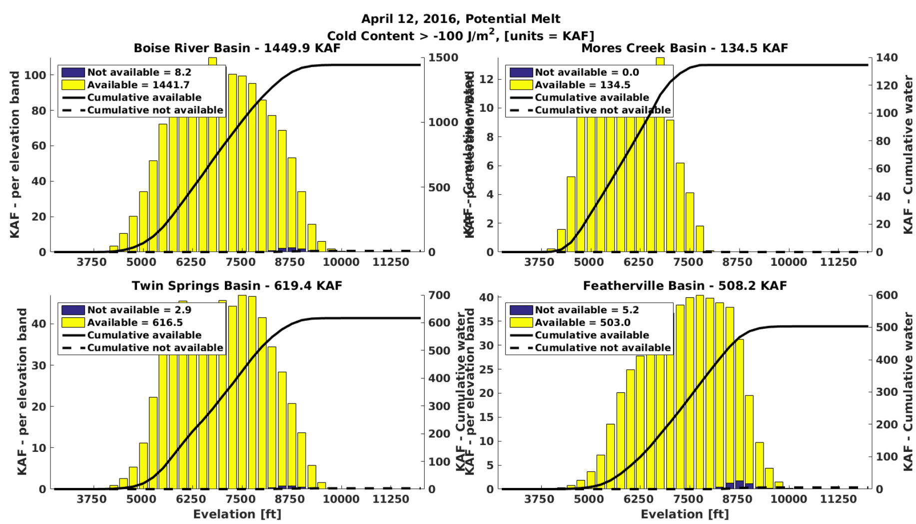

Figure 3: Potential water available or not available for melt as a function of elevation. Yellow indicates the total water volume potential from elevations where the snowpack is ready or already melting. The solid and dashed lines are the cumulative sum of water volume.

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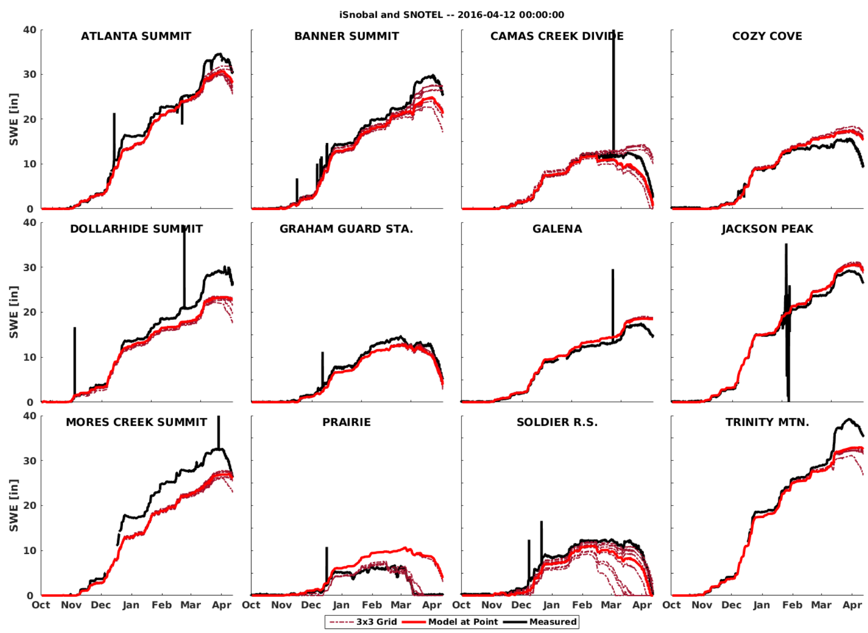

Figure 4: Validation of iSnobal results with 9 SNOTEL locations. Measured SWE in black, modeled SWE at the measurement location in red, and dashed lines represent a 300 meter by 300 meter (8 total model grid cells) around the measurement location. Scale differences exist between 7 m^2 pillow and 1,000 m^2 model cell and may account for some of the differences.

4 Weekly Changes

Comparing the changes between the last model run on April 7, 2016 and the current model run on April 12, 2016.

- All elevations showed a decrease in SWE, ranging **up to 4 inches of loss** (Figure 5).
- Large range in SWE change (**0 to 7 inches of loss**) due to warm daytime and night time temperatures with clear conditions. Larger SWE decrease for solar aspects (Figure 6).
- The change in water volume of BRB was estimated at **-181.7 KAF**, with more melt beginning at higher elevations (Figure 7).
- Snow water input (SWI) from rain on soil or melt from the bottom of the snowpack is estimated at **184.8 KAF** and is the amount of water entering the hydrologic system (Figure 8)

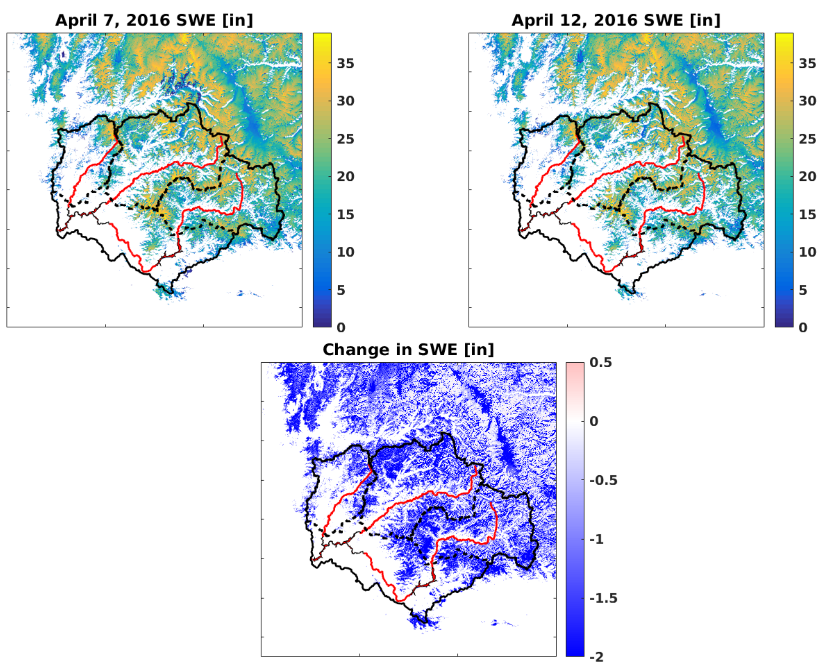

Figure 5: Current modeled SWE compared with last week's model results.

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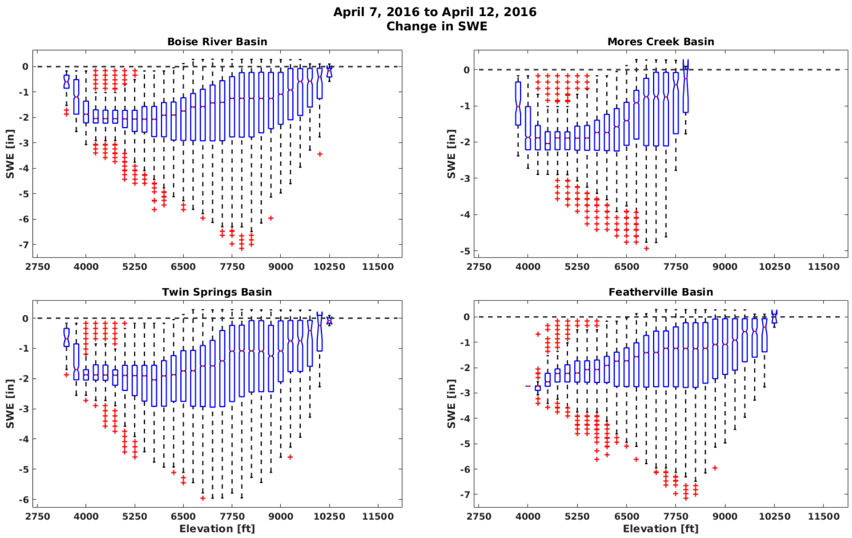

Figure 6: Current modeled SWE change since last week's model results as a function of elevation. Central mark is the median, edges of the box are 25th and 75th percentiles, the whiskers cover 99% of the data, with outliers in red.

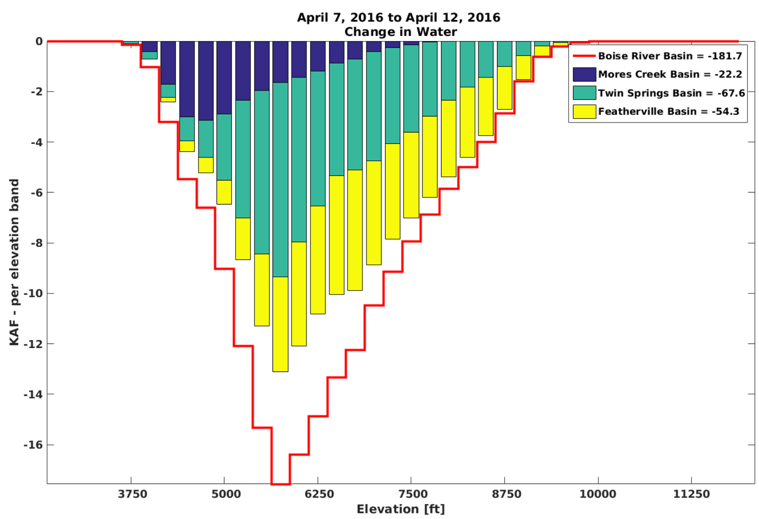

Figure 7: Change in water volume since last week's model results as a function of elevation, calculated from change in SWE. Legend shows net change for each basin.

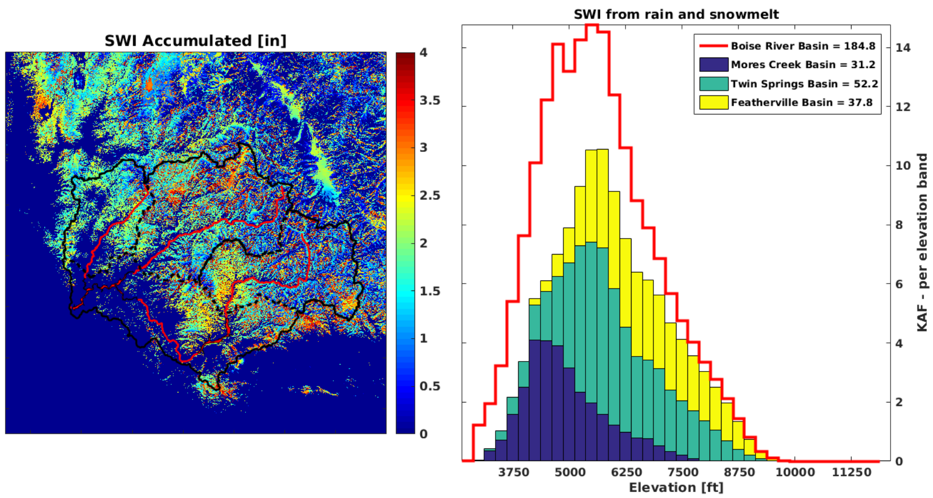

Figure 8: Snow water input (SWI) occurs from rain on the bare soil surface or melt from of the base of the snowpack to the soil surface. The left image shows the accumulated melt with total amount of SWI at each pixel since last model run. The right image shows SWI since last model result as a function of elevation and basin with net runoff for each basin in the legend.

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5 Short Term Forecast

A short term 72 hour forecast was produced by the Lab for Ecohydrology and Alternative Futuring (LEAF, leaf.boisestate.edu) at Boise State University using the Weather Research and Forecasting (WRF) model.

The forecast period is for April 12, 2016 06:00 UTC to April 15, 2016 06:00 UTC.

- An unsettled weather pattern beginning Tuesday afternoon will **add up to 1 inch** of SWE to upper elevations (Figure 9 and 10).
- Lower elevations bellow 7,750 ft will have the potential for **rain on snow, with an average of 1 inch** of SWE loss (Figure 10).
- The forecast is for warm temperatures this weekend, leading to an estimated at **-66.7 KAF** of water volume change (Figure 11).
- Snow water input (SWI) from rain on soil or melt from the bottom of the snowpack is estimated at **151 KAF** (Figure 12)

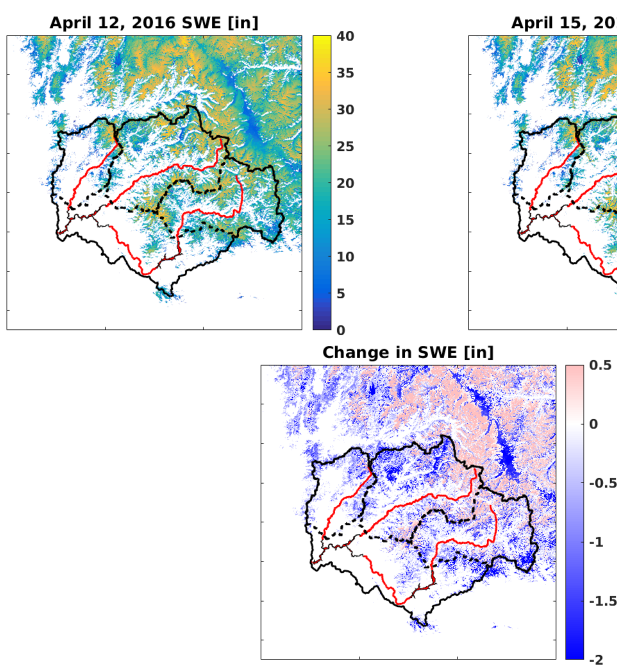

Figure 9: Current modeled SWE compared with 72 hour forecast model results.

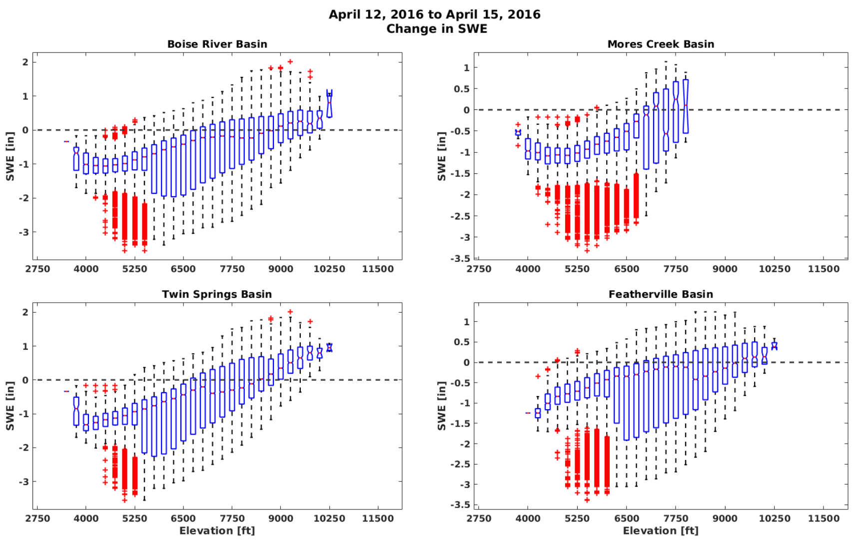

Figure 10: Forecasted model SWE change since as a function of elevation. Central mark is the median, edges of the box are 25th and 75th percentiles, the whiskers cover 99% of the data, with outliers in red.

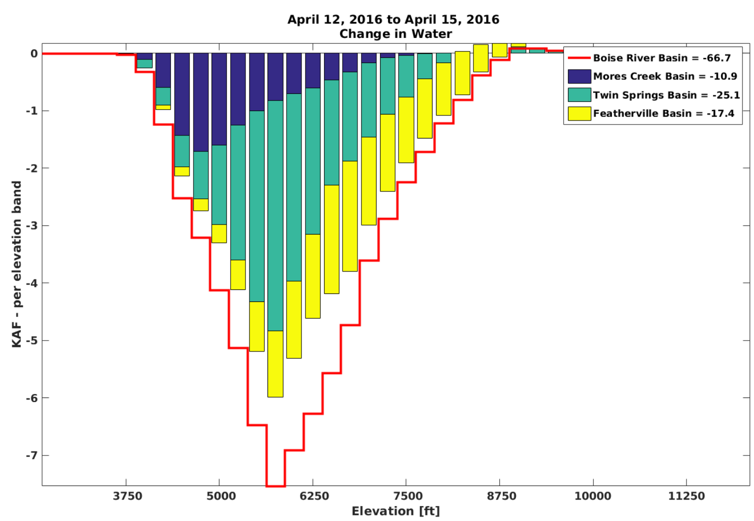

Figure 11: Forecasted change in water volume as a function of elevation, calculated from change in SWE. Legend shows net change for each basin.

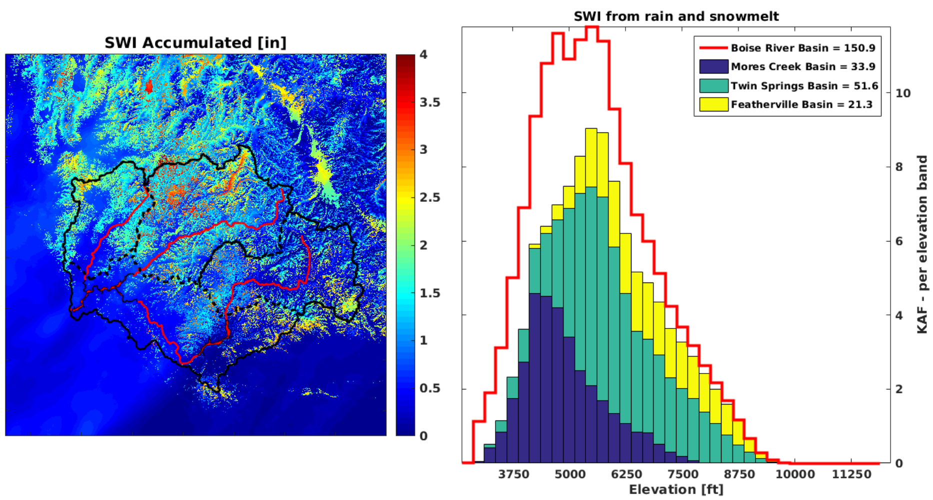

Figure 12: Snow water input (SWI) occurs from rain on the bare soil surface or melt from of the base of the snowpack to the soil surface. The left image shows the forecasted accumulated melt with total amount of runoff at each pixel. The right image shows forecasted runoff as a function of elevation and basin with net runoff for each basin in the legend.