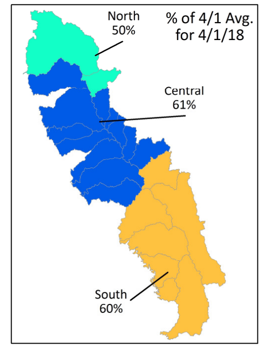
Real-Time Spatial Estimates of Snow-Water Equivalent (SWE)

Sierra Nevada Mountains, California
April 1, 2018



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Summary of current conditions

The map on the right shows mean spatial SWE above 5000' for 3 regions in the Sierra Nevada and corresponds to a daily map released by the CA DWR, which uses snow sensor data. Unlike the CA DWR map this map only includes the Feather and the Truckee in the North region. Snow extent could be low on the west side and around Lake Tahoe in the trees. The satellite can't always "see" snow in those areas. Currently the regression model could be underestimating SWE in higher elevations. Snow levels have increased in elevation since the last report and snow depths have increased at higher elevations. Tables 1 and 2 are showing decreases in SWE in the lower elevations between the March 19th report and this report. That is due to model overestimations in the lower elevations for the March 19th report. Lower elevation estimates should be more accurate for this report. Percent of averages should also be more accurate for this report. March 19th percent of average values have been updated for this report. Disregard percent of average values in the March 19th report.

About this report

This is a research product that provides near-real-time (NRT) estimates of snow-water equivalent (SWE) at a spatial resolution of 500 m for the Sierra Nevada in California over the latter portion of the snow season (February—June), approximately every 2 weeks. Due to processing time, this report will typically be released 2-3 days after the date at the top of the report. A similar experimental research product, covering the Intermountain West, makes its debut this season and will be distributed to water managers in Colorado, Utah and Wyoming.

The spatial SWE analysis method for the Sierra Nevada uses the following data as inputs:

- Operationally measured in-situ SWE from all CA snow gage sensor sites that have data available
- NRT MODSCAG (per pixel fractional snow-covered area or fSCA) data from the most recent cloud-free MODIS satellite image
- Physiographic information (elevation, latitude, upwind mountain barriers, slope, etc.)
- Historical daily SWE patterns (2000-2014) retrospectively generated using historical MODSCAG data, and an energy-balance model that back-calculates SWE given the fSCA timeseries and meltout date for each pixel

The use of historical SWE patterns provides more accurate estimation of current SWE than a method that interpolates between snow sensor sites using physiographic information alone (Schneider and Molotch, 2016). This method also allows for estimation of SWE values for elevations below and above the elevational extent of the snow gage sensor network. For more details on the estimation method, see the Methods section below.

Data availability for this report

99 snow gage sites in the Sierra Nevada network were recording SWE values out of a total of 114 sites. The locations of sensors that are offline (shown in red in Figure 3, left map) are mostly higher elevation. Out of 114 sites, 98 were reporting SWE on the ground, 1 was reporting 0 SWE, and 14 were offline.

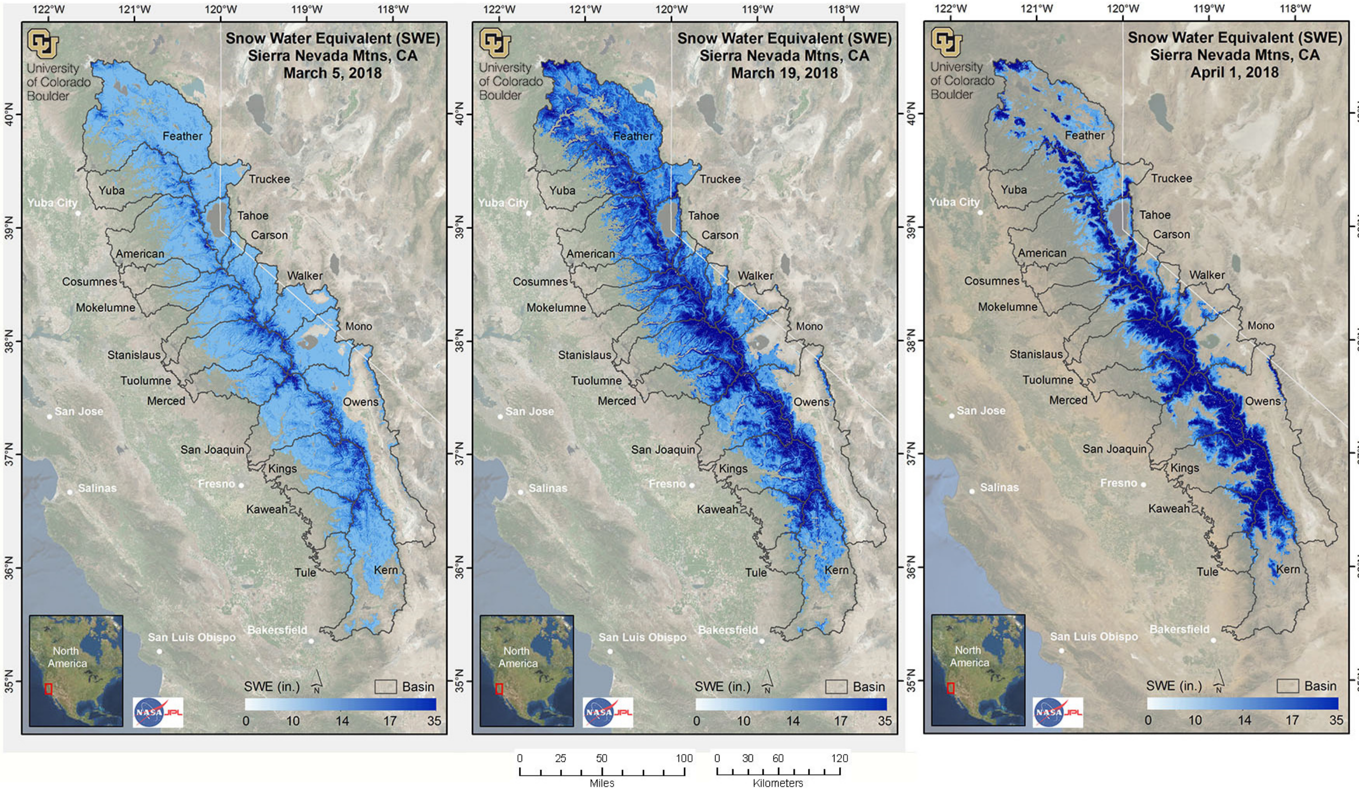

Figure 1. Estimated SWE across the Sierra Nevada. *SWE amounts for March 5, 2018 (left), March 19th* (middle), and April 1st (right).

The value of spatially explicit estimates of SWE

Snowmelt makes up the large majority (~60-85%) of the annual streamflow in the Sierra Nevada. The spatial distribution of snow-water equivalent (SWE) across the landscape is complex. While broad aspects of this spatial pattern (e.g., more SWE at higher elevations and on north-facing exposures) are fairly consistent, the details can vary a lot from year to year, influencing the magnitude and timing of snowmelt-driven runoff.

SWE is operationally monitored at just over a hundred snow gage sensor sites spread across the Sierra Nevada, providing a critical first-order snapshot of conditions, and the basis for runoff forecasts from the CA DWR and NOAA. However, conditions at snow sensor sites (e.g., percent of normal SWE) may not be representative of conditions in the large areas between these point measurements, and at elevations above and below the range of the sensor sites. The spatial snow analysis creates a detailed picture of the spatial pattern of SWE using snow sensors, satellite, and other data, extending beyond the snow sensor sites to the unsampled areas. This makes it possible to identify unusual spatial patterns, and if significant differences from sensor-observed SWE conditions are present. More generally, the spatial snow analysis clearly shows the dynamic nature of the snow-water resource across both time and space.

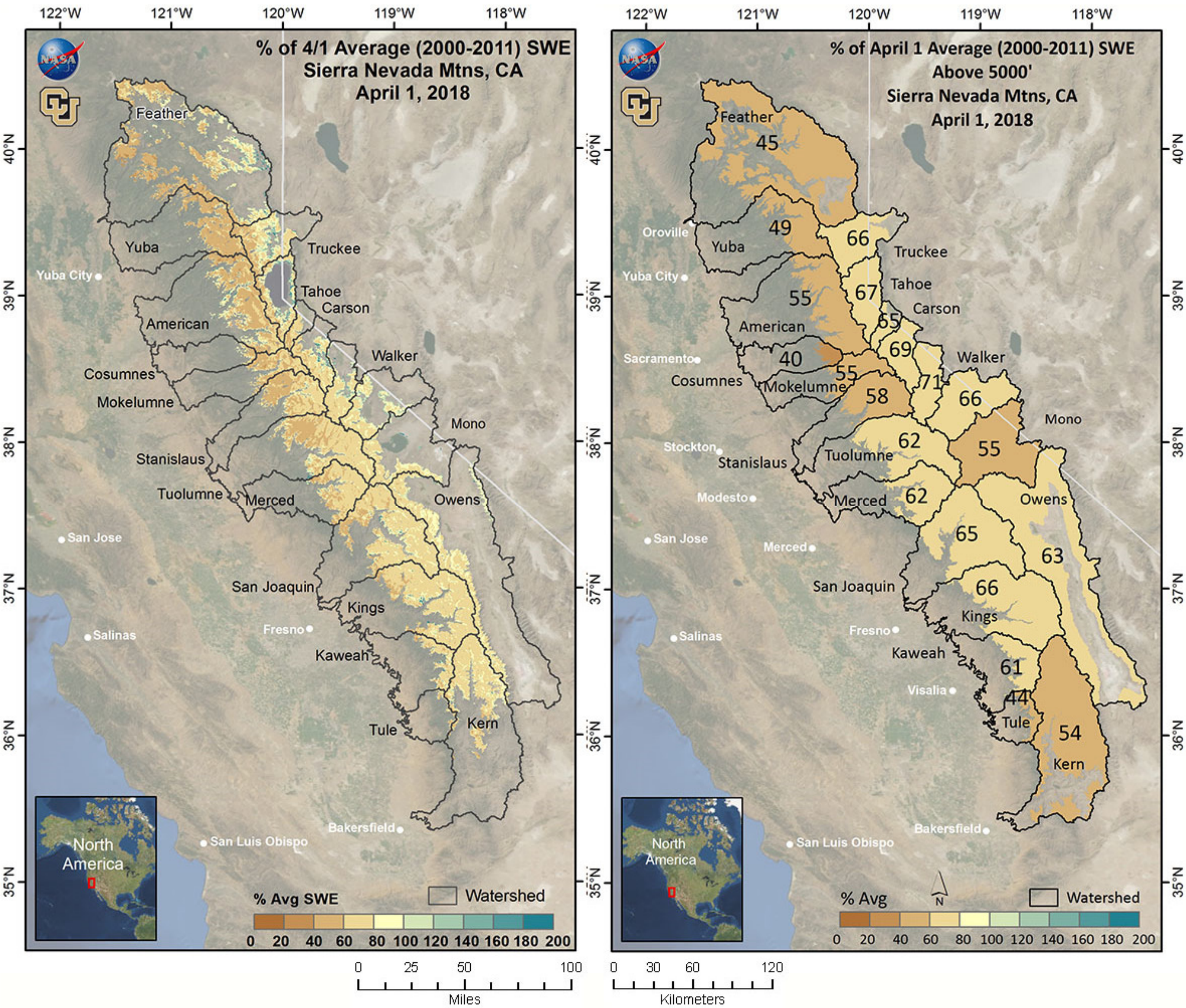

Figure 2*. *Estimated % of average SWE across the Sierra Nevada. *Percent of average (2000-2011) SWE for April 1, 2018 for the Sierra Nevada, calculated for each pixel (left) and basinwide (right). Basinwide percent of average is calculated across all model pixels >5000' elevation.*

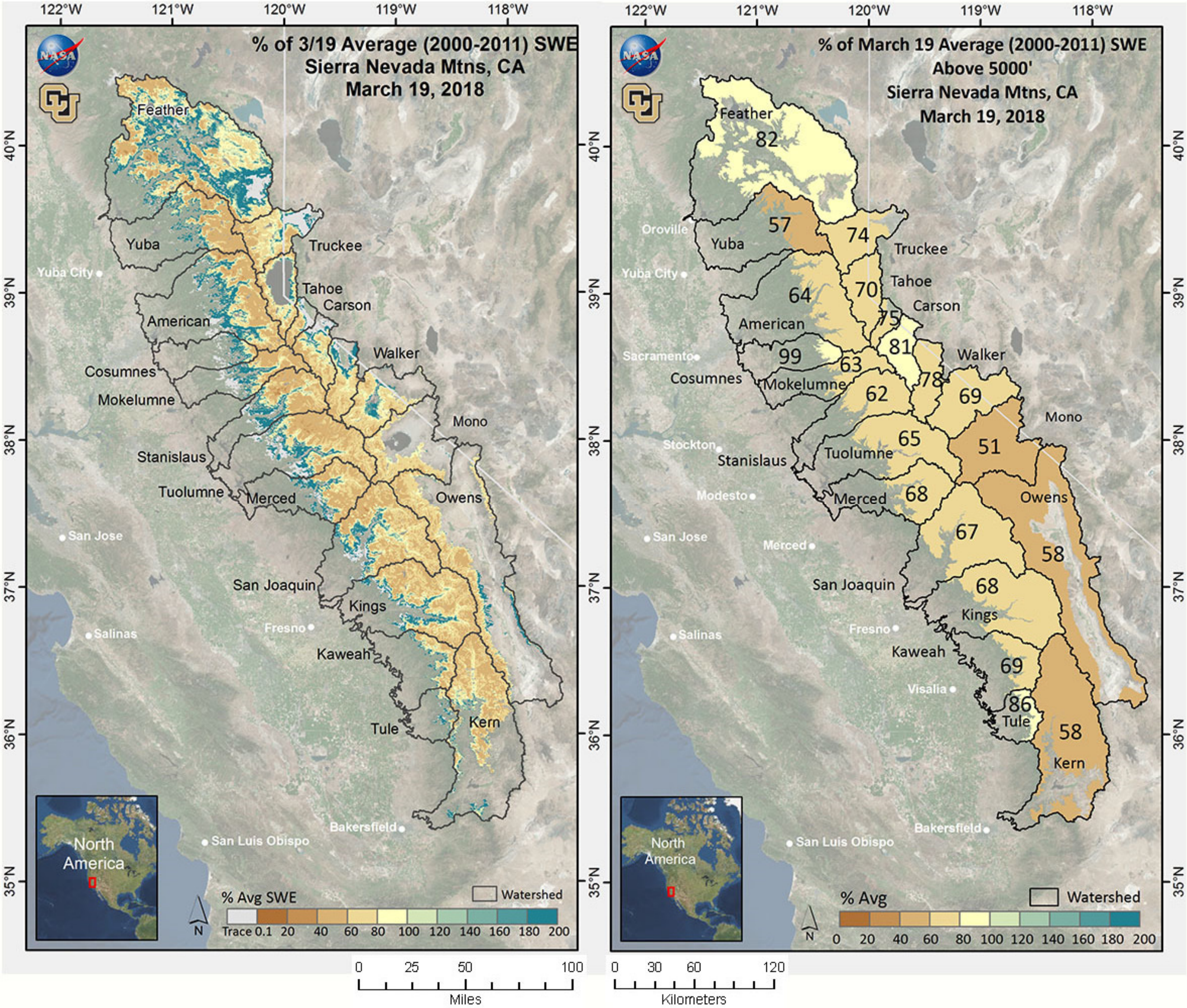

***Figure 3*. Estimated % of average SWE across the Sierra Nevada.** *Percent of average (2000-2011) SWE for March 19, 2018 for the Sierra Nevada, calculated for each pixel (left) and basinwide (right). Basinwide percent of average is calculated across all model pixels >5000' elevation.*

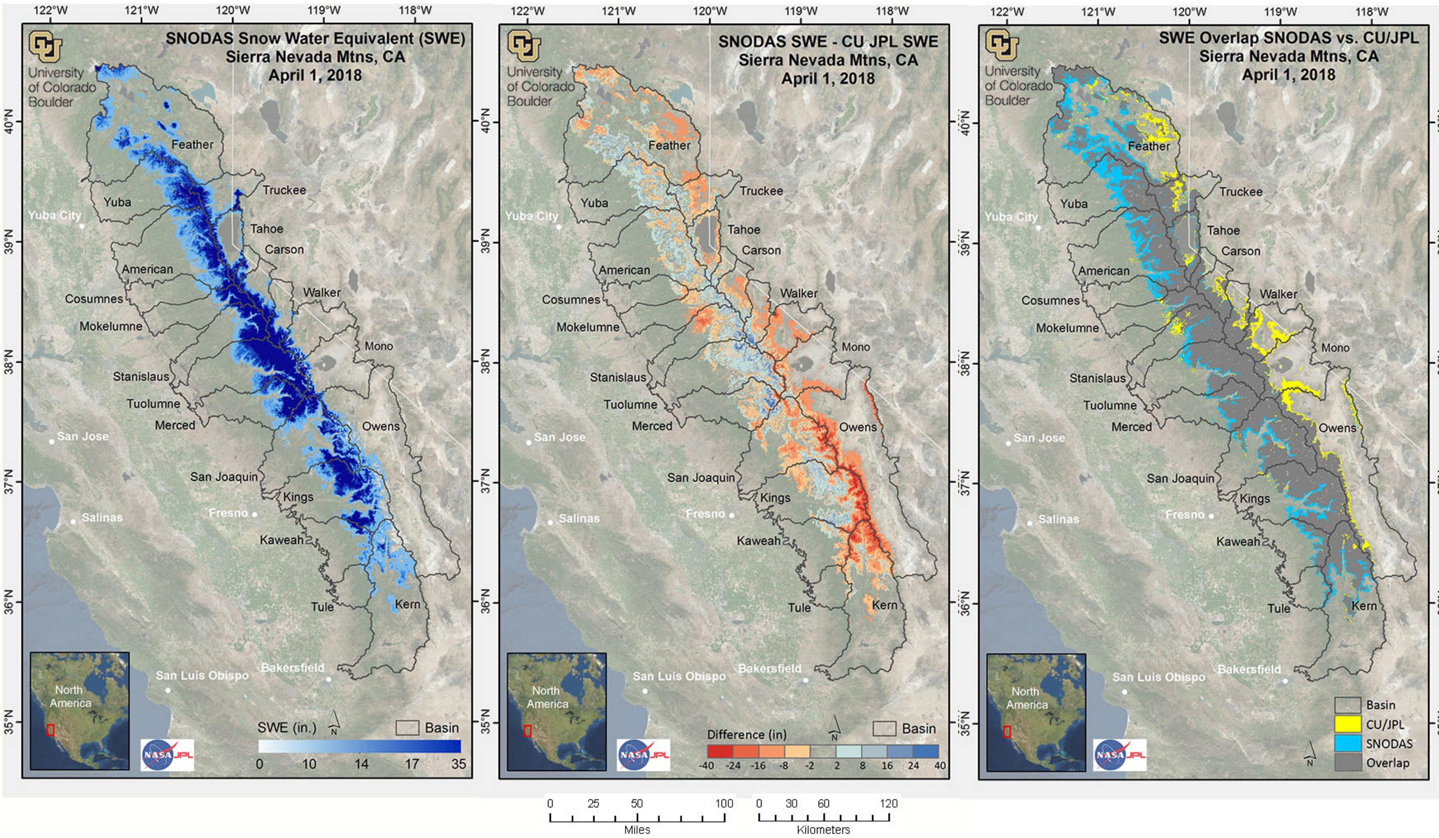

Figure 4. Comparison of CU/JPL regression SWE vs. SNODAS SWE for the Sierra Nevada. *The map on the left shows April 1st SNODAS SWE. The middle map shows the difference between the April 1st SNODAS SWE and CU/JPL regression SWE estimate. Red pixels denote areas where SNODAS SWE is less than CU/JPL SWE and blue pixels show areas where SNODAS SWE is higher than CU/JPL SWE. The map on the right shows the extent of the snow-covered for the SNODAS SWE product and the CU/JPL SWE estimate. Yellow pixels show where the location of CU/JPL snow extends beyond the location of the SNODAS snow extent. Blue pixels show where the SNODAS snow extends beyond the CU/JPL snow extent. Gray areas show the overlap between the 2 products.*

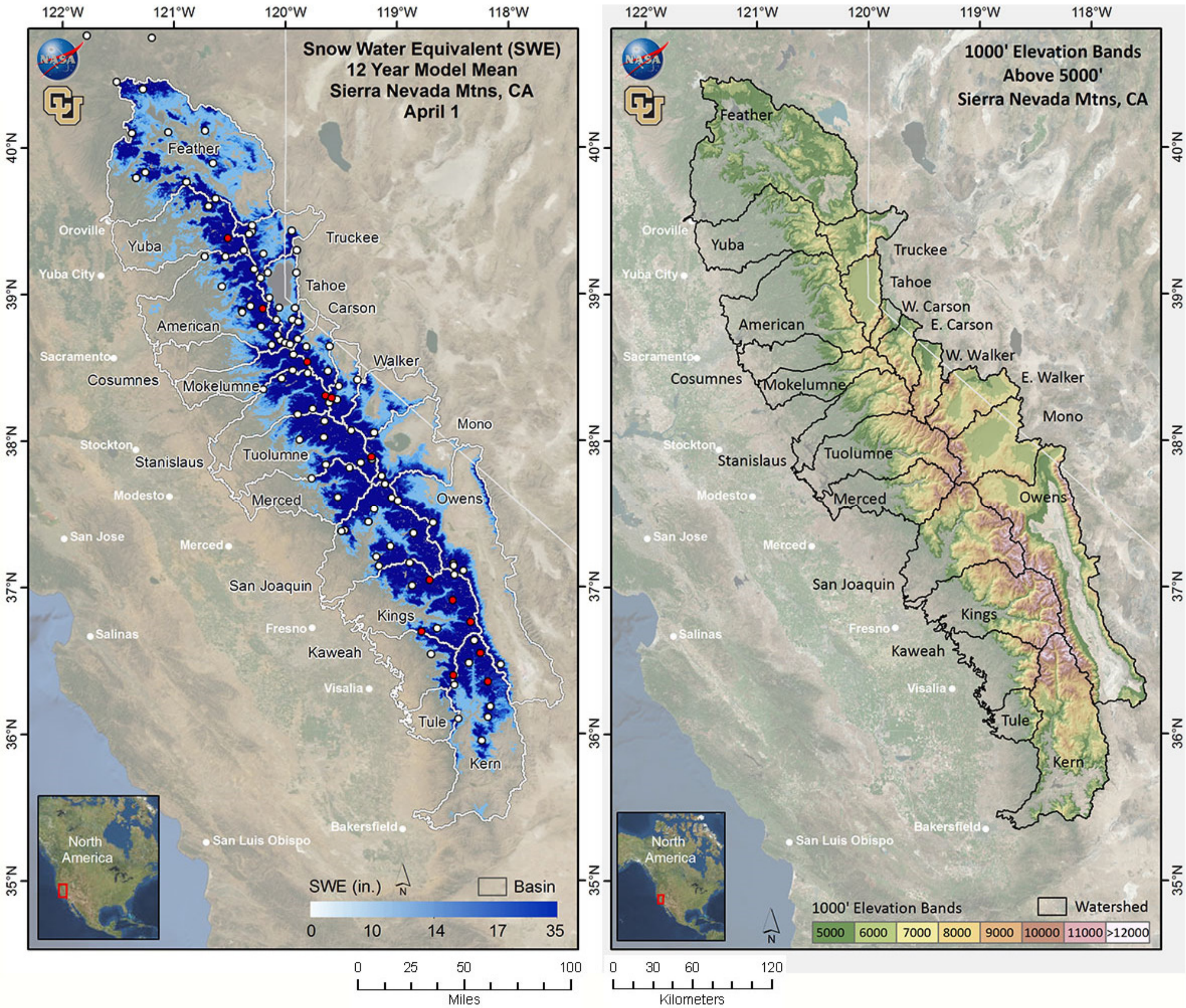

Figure 5. Mean SWE and Elevation Bands for the Sierra Nevada. *Mean SWE (2000-2011) amounts for April 1st (left), and Banded Elevation map identifies basins used in this report (black boundaries) and 1000' elevation bands (colored shading) that match those used in Table 1 and Table 2. Map on left shows snow gage sensor sites recording SWE on April 1, 2018 (white) and sites that were offline are shown in red.*

Methods

The spatial SWE estimation method is described in Schneider and Molotch (2016). The method uses linear regression in which the dependent variable is derived from the operationally measured in situ SWE from all online snow sensor sites in the domain. The snow sensor SWE observations are scaled by the fractional snow-covered area across the 500 m pixel containing that snow sensor site before being used in the linear regression model.

The following independent variables (predictors) enter into the linear regression model:

- A near-real-time cloud-free MODIS satellite image which has been processed using the MODIS Snow Cover and Grain size (MODSCAG) fractional snow-covered area algorithm program (Painter, et. al. 2009, snow.jpl.nasa.gov)
- Physiographic variables that affect snow accumulation, melt, and redistribution, including elevation, latitude, upwind mountain barriers, slope, etc. See Figure 2 in Schneider and Molotch (2016) for the full set of these variables.

- The historical daily SWE pattern (2000-2014) retrospectively generated using historical MODSCAG data, and an energy-balance model that back-calculates SWE given the fractional Snow-Covered Area (fSCA) time series and meltout date for each pixel. See Guan, et. al., 2013 and the additional references for details. (For computational efficiency, only one image from either the 1st or 15th of each month during the 2000-2014 period that best matches the real-time snow sensor-observed pattern is selected as an independent variable.)

The real-time regression model for this date has been validated by cross-validation, whereby 10% of the snow sensor data are randomly removed and the model prediction is compared to the measured value at the removed snow sensor stations. This is repeated 30 times to get an average R-squared value, which denotes how closely the model fits the snow sensor data. During development of this regression method in the Intermountain West, the model was also validated against independent SWE data collected in NRCS snow surveys at 9 locations in Colorado and an intensive field survey in north-central Colorado.

Table 1. Estimated SWE by basin. *The basinwide SWE values and averages, are across all pixels at elevations >5000'. Shown are April 1st percent of April 1st average and March 19th percent of March 19th average SWE (between 2000-2011), April 1st mean SWE from SNODAS, March 19th and April 1st mean SWE, and the difference between March 19th and April 1st SWE summarized for each basin.*

Basin	3/19/18 % 3/19 Avg.	4/1/18 % 4/1 Avg.	4/1/18 SNODAS (in)	3/19/18 SWE (in)	4/1/18 SWE (in)	3/19 thru 4/1/18 Chg. in SWE (in)	Area (mi^2) > 5000'
American	64	55	14.0	15.2	12.7	-2.5	798.0
Cosumnes	99	40	3.9	11.9	5.2	-6.8	87.8
E Carson	81	69	8.6	14.3	10.6	-3.6	400.2
E Walker	69	66	2.3	8.7	6.2	-2.5	801.4
Feather	82	45	4.7	14.2	6.5	-7.7	2,086.3
Kaweah	69	61	6.9	10.9	9.6	-1.3	315.9
Kern	58	54	2.6	7.4	6.2	-1.3	1,770.6
Kings	68	66	11.0	15.1	14.8	-0.3	1,220.0
Merced	68	62	14.4	14.9	13.7	-1.2	535.7
Mokelumne	63	55	12.8	15.4	13.4	-2.0	316.3
Mono	51	55	2.0	5.6	4.5	-1.0	1,088.0
Owens	58	63	1.1	6.1	5.5	-0.6	2,167.6
San Joaquin	67	65	10.0	15.4	15.0	-0.4	1,226.8
Stanislaus	62	58	13.4	15.4	14.2	-1.2	558.0
Tahoe	70	67	11.6	15.0	13.1	-1.9	509.8
Truckee	74	66	7.9	14.1	10.2	-3.9	556.2
Tule	86	44	1.6	6.1	3.0	-3.1	138.2
Tuolumne	65	62	18.2	16.1	15.4	-0.7	908.9
W Carson	75	65	11.2	13.6	10.9	-2.7	123.9
W Walker	78	71	8.6	12.5	9.9	-2.6	432.7
Yuba	57	49	14.4	15.5	13.1	-2.4	518.9

Table 2. Estimated SWE by basin and elevation band. *Elevation bands begin at 5000' and extend past the highest point in the basin. Note that the area of the highest 2-5 bands is typically much smaller than the lower bands. Shown are April 1st percent of April 1st average and March 19th percent of March 19th average SWE (between 2000-2011), April 1st mean SWE from SNODAS, March 19th and April 1st mean SWE, and the difference between March 19th and April 1st SWE summarized for each 1000' elevation band inside each basin.*

Basin	Elevation Band	3/19/18 % 3/19 Avg.	4/1/18 % 4/1 Avg.	4/1/18 SNODAS (in)	3/19/18 SWE (in)	4/1/18 SWE (in)	3/19 thru 4/1/18 Chg. in SWE (in)	Area Sq Mi
American	5000-6000'	97	49	9.3	13.3	6.1	-7.2	295.5
	6000-7000'	56	52	12.9	14.4	12.6	-1.8	261.0
	7000-8000'	53	57	18.2	17.2	19.0	1.9	166.3
	8000-9000'	58	63	26.7	21.1	24.6	3.5	67.8
	9000-10,000'	58	65	32.7	24.4	29.5	5.2	8.6
Cosumnes	5000-6000'	162	23	2.8	10.9	2.1	-8.8	57.9
	6000-7000'	67	54	5.4	13.7	10.1	-3.6	22.9
	7000-8000'	50	52	8.2	15.0	15.5	0.5	6.4
E. Carson	5000-6000'	-	2	0.0	9.5	0.0	-9.5	65.9
	6000-7000'	129	57	0.4	13.3	3.2	-10.0	90.7
	7000-8000'	71	73	6.2	14.2	11.7	-2.5	104.8
	8000-9000'	60	68	16.5	16.0	17.7	1.7	95.2
	9000-10,000'	64	73	24.8	19.1	22.3	3.2	33.8
	10,000-11,000'	65	76	29.1	20.6	24.8	4.2	10.3
	> 11,000'	59	72	22.4	21.1	27.5	6.5	0.3
E. Walker	5000-6000'	0	6	0.0	0.0	0.0	0.0	21.5
	6000-7000'	107	36	0.0	2.7	0.1	-2.7	211.7
	7000-8000'	72	74	0.1	7.7	2.1	-5.5	254.4
	8000-9000'	66	76	1.9	12.1	9.9	-2.2	185.8
	9000-10,000'	64	75	10.4	15.6	17.4	1.8	76.6
	10,000-11,000'	63	76	14.2	19.8	23.8	4.0	40.6
	11,000-12,000'	62	76	8.8	20.2	25.6	5.4	10.3
	> 12,000'	62	31	6.5	20.9	26.9	6.0	0.3
Feather	5000-6000'	101	55	3.4	13.5	3.3	-10.2	1,259.3
	6000-7000'	68	61	5.8	15.0	10.2	-4.7	706.5
	7000-8000'	57	67	11.6	16.7	17.1	0.4	114.3
	8000-9000'	61	0	19.4	21.1	23.9	2.8	3.7
Kaweah	5000-6000'	80	14	0.1	1.9	0.0	-1.9	62.1
	6000-7000'	107	54	2.0	8.3	0.8	-7.5	59.5
	7000-8000'	79	67	5.5	11.7	7.3	-4.4	58.6
	8000-9000'	64	70	11.2	13.4	14.7	1.3	55.6
	9000-10,000'	62	68	15.8	15.6	18.6	3.0	43.6
	10,000-11,000'	58	68	12.4	19.0	24.5	5.5	29.8
	11,000-12,000'	56	70	7.6	20.1	27.0	6.9	8.1
	> 12,000'	51	0	8.3	18.6	26.5	7.9	0.2
Kern	5000-6000'	74	1	0.0	0.6	0.0	-0.6	294.4
	6000-7000'	78	12	0.1	3.3	0.0	-3.2	369.9
	7000-8000'	52	46	0.7	5.6	0.9	-4.7	336.4
	8000-9000'	56	72	4.3	10.2	7.0	-3.2	315.5
	9000-10,000'	60	72	8.6	12.4	14.1	1.7	187.5
	10,000-11,000'	57	72	6.1	14.5	18.7	4.1	127.9
	11,000-12,000'	56	76	4.9	17.5	23.7	6.2	92.8
	> 12,000'	59	2	3.1	19.5	26.6	7.1	44.2

Basin	Elevation Band	3/19/18 % 3/19 Avg.	4/1/18 % 4/1 Avg.	4/1/18 SNODAS (in)	3/19/18 SWE (in)	4/1/18 SWE (in)	3/19 thru 4/1/18 Chg. in SWE (in)	Area Sq Mi
Kings	5000-6000'	302	19	0.3	10.7	0.1	-10.6	101.3
	6000-7000'	117	54	2.1	12.0	1.8	-10.2	131.6
	7000-8000'	72	69	7.9	12.4	8.4	-4.1	168.6
	8000-9000'	65	72	15.6	13.6	13.8	0.2	216.8
	9000-10,000'	63	71	19.9	15.1	17.4	2.3	209.7
	10,000-11,000'	59	72	15.0	17.9	22.6	4.7	189.6
	11,000-12,000'	59	74	7.5	20.2	26.7	6.5	150.5
	> 12,000'	58	6	4.7	21.1	28.7	7.6	51.2
Merced	5000-6000'	339	39	0.4	10.7	0.3	-10.4	70.3
	6000-7000'	106	59	5.0	12.6	4.6	-8.1	78.2
	7000-8000'	61	65	9.9	13.3	12.2	-1.1	135.0
	8000-9000'	58	68	16.6	14.9	16.9	2.0	118.6
	9000-10,000'	59	69	32.2	18.0	21.8	3.8	83.2
	10,000-11,000'	59	71	28.0	22.4	28.4	5.9	37.3
	11,000-12,000'	59	70	17.6	25.8	33.2	7.5	11.5
	> 12,000'	58	23	14.0	28.0	36.8	8.8	1.4
Mokelumne	5000-6000'	119	52	0.7	12.0	2.3	-9.8	81.0
	6000-7000'	64	58	5.2	14.0	9.9	-4.1	63.8
	7000-8000'	53	63	17.6	16.1	17.7	1.6	87.0
	8000-9000'	56	66	25.3	18.9	22.4	3.4	75.4
	9000-10,000'	59	11	30.1	21.9	26.3	4.4	7.9
Mono	6000-7000'	16	18	0.0	0.4	0.1	-0.3	378.1
	7000-8000'	39	57	0.0	3.4	0.8	-2.5	396.2
	8000-9000'	56	76	0.9	9.7	7.2	-2.5	175.3
	9000-10,000'	63	72	10.7	14.8	16.9	2.1	63.0
	10,000-11,000'	62	73	18.6	20.3	24.7	4.4	45.8
	11,000-12,000'	62	74	13.4	21.9	27.3	5.3	25.8
	> 12,000'	60	0	8.8	21.7	28.1	6.4	4.5
Owens	5000-6000'	-	0	0.0	1	0	-1	424.2
	6000-7000'	45	20	0.0	1	0	-1	412.9
	7000-8000'	46	50	0.0	3.9	1.0	-3.0	462.7
	8000-9000'	56	67	0.9	7.6	4.9	-2.7	258.5
	9000-10,000'	61	76	3.0	11.2	10.4	-0.8	190.4
	10,000-11,000'	60	78	4.6	13.7	16.2	2.5	195.1
	11,000-12,000'	61	80	4.0	17.1	21.9	4.8	145.5
	> 12,000'	61	3	2.5	18.3	24.7	6.4	79.9
San Joaquin	5000-6000'	205	32	0.1	10.7	0.2	-10.6	141.0
	6000-7000'	85	60	3.1	11.8	3.8	-8.0	179.5
	7000-8000'	64	69	5.5	12.5	10.6	-1.8	211.4
	8000-9000'	60	71	10.1	14.8	16.7	1.9	194.4
	9000-10,000'	61	72	20.9	17.3	20.6	3.3	199.7
	10,000-11,000'	61	72	18.5	20.4	25.3	4.9	157.9
	11,000-12,000'	60	75	11.3	21.7	28.4	6.6	116.7
	> 12,000'	61	24	6.5	22.1	29.5	7.3	25.8

Basin	Elevation Band	3/19/18 % 3/19 Avg.	4/1/18 % 4/1 Avg.	4/1/18 SNODAS (in)	3/19/18 SWE (in)	4/1/18 SWE (in)	3/19 thru 4/1/18 Chg. in SWE (in)	Area Sq Mi
Stanislaus	5000-6000'	126	53	1.1	11.6	2.2	-9.4	105.5
	6000-7000'	63	58	3.9	13.5	9.9	-3.6	134.9
	7000-8000'	52	65	13.7	14.8	16.0	1.2	142.9
	8000-9000'	57	68	26.4	18.4	21.3	3.0	112.9
	9000-10,000'	59	67	31.2	21.6	25.9	4.4	49.1
	10,000-11,000'	58	71	29.2	24.9	31.1	6.2	11.8
	> 11,000'	58	68	18.2	25.8	33.5	7.7	0.3
Tahoe	6000-7000'	91	65	4.0	12.7	7.0	-5.7	319.0
	7000-8000'	65	67	12.5	15.0	13.9	-1.1	105.7
	8000-9000'	59	72	20.6	17.8	20.3	2.5	68.4
	9000-10,000'	62	75	26.9	19.9	24.0	4.0	15.8
	10,000-11,000'	65	68	22.9	21.6	26.3	4.7	0.6
Truckee	5000-6000'	151	68	0.2	12.3	2.9	-9.4	133.5
	6000-7000'	75	62	5.8	13.5	8.9	-4.6	245.4
	7000-8000'	58	67	13.0	15.6	15.3	-0.3	126.9
	8000-9000'	56	78	22.3	17.1	20.3	3.2	39.7
	9000-10,000'	64	80	31.7	20.4	25.2	4.8	9.4
	10,000-11,000'	65	0	27.6	21.5	27.4	5.9	0.4
Tule	5000-6000'	-	6	0.0	2.8	0.0	-2.8	51.4
	6000-7000'	108	42	0.4	5.1	0.3	-4.8	40.8
	7000-8000'	68	65	2.9	9.5	5.6	-4.0	26.7
	8000-9000'	65	69	6.4	12.5	12.7	0.2	14.5
	9000-10,000'	61	64	9.5	13.2	16.3	3.0	4.3
	10,000-11,000'	51	22	10.9	12.6	16.8	4.2	0.1
Tuolumne	5000-6000'	166	59	1.9	11.9	1.6	-10.3	167.2
	6000-7000'	79	58	10.6	13.3	8.8	-4.6	139.8
	7000-8000'	55	62	16.3	14.2	14.3	0.0	150.0
	8000-9000'	55	66	25.3	16.8	19.3	2.5	164.1
	9000-10,000'	58	69	32.1	19.5	23.5	4.0	173.0
	10,000-11,000'	59	72	25.7	21.8	27.2	5.4	87.1
	11,000-12,000'	61	73	13.7	23.5	29.9	6.4	23.9
	> 12,000'	59	0	8.7	24.2	32.0	7.8	2.8
W. Carson	5000-6000'	-	41	0.0	8.7	0.0	-8.7	24.9
	6000-7000'	135	63	0.9	12.3	2.0	-10.4	13.7
	7000-8000'	64	66	12.2	13.8	11.8	-2.0	39.2
	8000-9000'	59	71	17.9	15.7	17.3	1.6	33.2
	9000-10,000'	61	72	23.3	17.9	21.1	3.1	11.1
	10,000-11,000'	57	0	23.5	18.0	23.3	5.3	1.1
W. Walker	5000-6000'	-	36	0.0	3	0	-3	78.8
	6000-7000'	199	76	0.0	11.5	0.8	-10.7	68.7
	7000-8000'	85	73	1.2	13.0	7.3	-5.7	97.5
	8000-9000'	64	70	11.7	13.7	13.8	0.1	83.6
	9000-10,000'	60	71	24.9	17.7	20.9	3.2	73.5
	10,000-11,000'	61	74	25.5	21.4	26.0	4.7	28.8
	> 11,000'	60	36	15.9	20.6	26.3	5.7	2.3
Yuba	5000-6000'	75	50	10.5	13.7	6.0	-7.7	191.7
	6000-7000'	50	56	15.3	15.7	15.4	-0.2	214.6
	7000-8000'	51	66	18.9	17.9	20.4	2.5	110.0
	8000-9000'	60	53	26.5	23.1	26.7	3.5	3.8

Location of Reports and Excel Format Tables

ftp://snowserver.colorado.edu/pub/fromLeanne/forCADWR/Near_Real_Time_Reports/

References

Guan, B., N. P. Molotch, D. E. Waliser, S. M. Jepsen, T. H. Painter, and J. Dozier. (2013). Snow water equivalent in the Sierra Nevada: Blending snow sensor observations with snowmelt model simulations. *Water Resources Research, Vol. 49, 5029–5046, doi:10.1002/wrcr.20387.*

Painter, T.H., K. Rittger, C. McKenzie, P. Slaughter, R. E. Davis and J. Dozier. (2009) Retrieval of subpixel snow covered area, grain size, and albedo from MODIS. *Remote Sensing of the Environment*, 113: 868-879.

Schneider D. and N.P. Molotch. (2016). Real-time estimation of snow water equivalent in the Upper Colorado River Basin using MODIS-based SWE reconstructions and SNOTEL data. *Water Resources Research*, 52(10): 7892-7910. DOI: 10.1002/2016WR019067.

Additional Historical Reconstructed SWE Sources

Molotch, N.P. (2009). Reconstructing snow water equivalent in the Rio Grande headwaters using remotely sensed snow cover data and a spatially distributed snowmelt model. *Hydrological Processes*, Vol. 23, doi: 10.1002/hyp.7206, 2009.

Molotch, N.P., and S.A. Margulis. (2008) Estimating the distribution of snow water equivalent using remotely sensed snow cover data and a spatially distributed snowmelt model: a multi-resolution, multi-sensor comparison. *Advances in Water Resources*, 31, 2008.

Molotch, N.P., and R.C. Bales. (2006). Comparison of ground-based and airborne snow-surface albedo parameterizations in an alpine watershed: impact on snowpack mass balance. *Water Resources Research*, VOL. 42, doi:10.1029/2005WR004522.

Molotch, N.P., and R.C. Bales. (2005). Scaling snow observations from the point to the grid-element: implications for observation network design. *Water Resources Research*, VOL. 41, doi: 10.1029/2005WR004229.

Molotch, N.P., T.H. Painter, R.C. Bales, and J. Dozier. (2004). Incorporating remotely sensed snow albedo into a spatially distributed snowmelt model. *Geophysical Research Letters*, VOL. 31, doi:10.1029/2003GL019063, 2004.