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

Western United States Region

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Introduction

Figure 1 below displays estimated SWE amounts across the Western United States. Detailed SWE maps (in JPG format) and summaries of SWE (in Excel format) by individual basin and elevation band accompany the report and are publicly available here. Please note that the basin-wide percent of long-term average from the spatial SWE estimates is not directly comparable with the SNOTEL basin-wide percent of average. A better comparison might be made with the percent of average in the elevation banded tables (linked below) that contain SNOTEL sites.

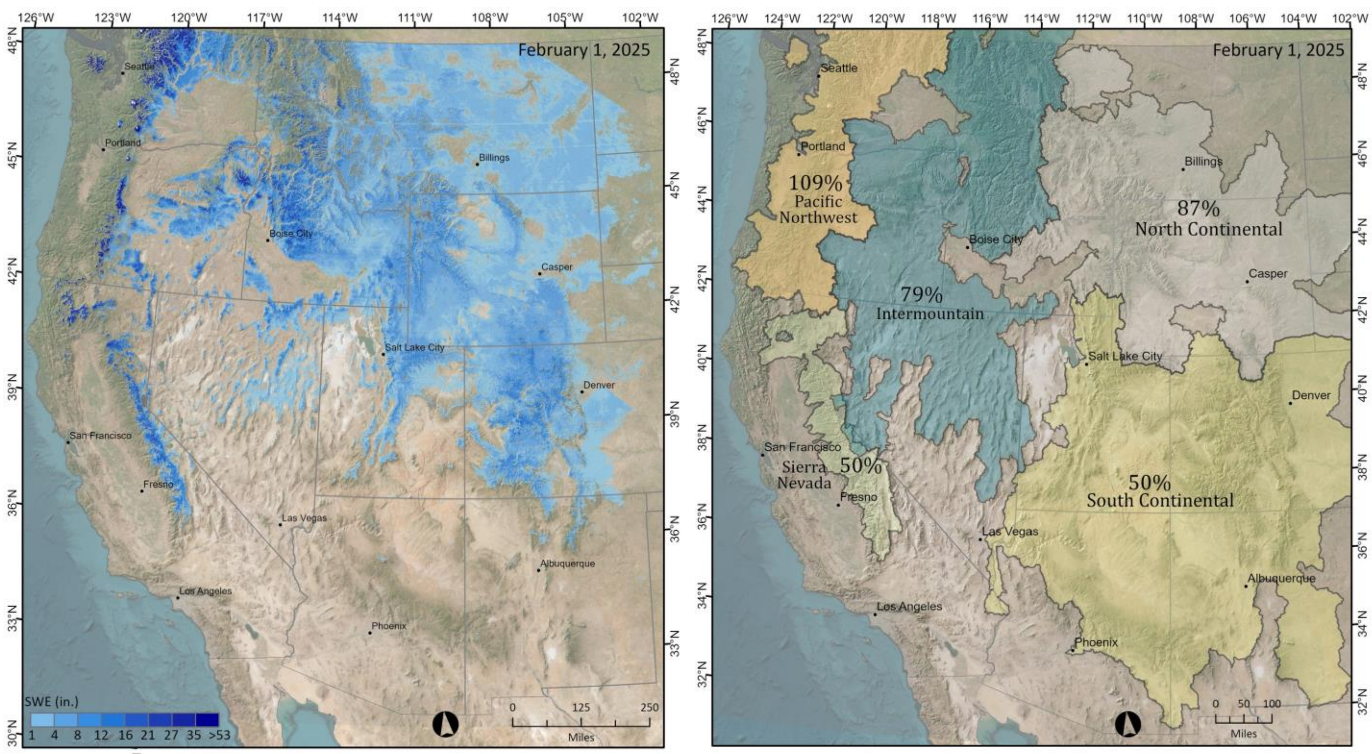

Figure 1. Estimated SWE and % of Average SWE across the Western U.S. SWE amounts across the entire Western region of the United States (left) and percent of long-term average (2001-2021) by five regions (right). Region boundaries are delineated based on Snowpack regimes of the Western United States (Trujillo and Molotch, 2014) and the Commission for Environmental Cooperation (CEC) Ecological Regions of North America, Level III [Commission for Environmental Cooperation, 2009, available at http://www.cec.org/north-american-environmental-atlas/terrestrial-ecoregions-level-iii/].

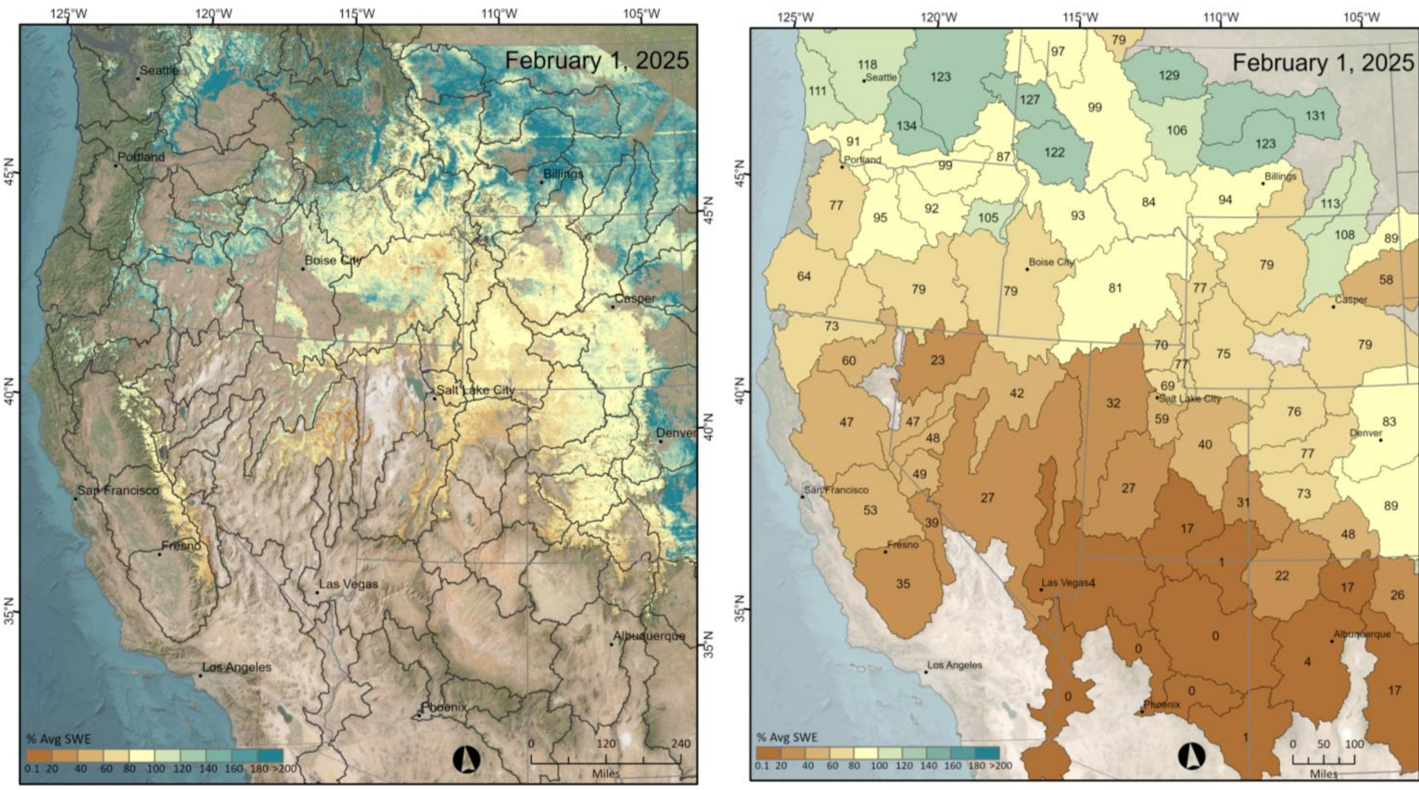

Figure 2. Estimated % of Average SWE across the Western U.S. Percent of long-term average (2001-2021) SWE calculated for each pixel (left) and by HUC-6 basin (right); integer within each watershed represents the percent of average SWE for the report date.

For detailed maps and tabular summaries of SWE and snowpack water storage volumes for specific regions and watersheds, click on the links below:

Pacific Northwest
North Continental
South Continental
Intermountain
Sierra Nevada
Elevation Banded SWE Tables

About this report

This is an experimental research product that provides near-real-time estimates of snow-water equivalent (SWE) at a spatial resolution of 500 meters for the Western region of the United States from mid-winter through the melt season. The report is typically released within a week of the date of data acquisition at the top of the report. A similar report covering the Sierra Nevada has been distributed to water managers in California since 2012.

The spatial SWE data fusion (SWE-fusion) analysis method for the Western U.S. uses the following data as inputs:

- In-situ SWE from all operational NRCS and CDEC snow pillow sites, and the CoCoRaHS network when appropriate
- Fractional snow-covered area (fSCA) data from recent cloud-free satellite images
- Physiographic information (elevation, latitude, upwind mountain barriers, slope, etc.)
- Historical daily SWE patterns (1985-2021) retrospectively generated using historical fSCA data and an energy-balance model that back-calculates SWE given the fSCA time-series and meltout date for each pixel
- Satellite-observed daily mean fractional snow-covered area (DMFSCA)

For more details see the *Methods* section below. Please be sure to read the *Data Issues / Caveats* section for a discussion of persistent challenges or flagged uncertainties of the SWE-fusion product.

Data availability for reporting

Snow pillows located throughout the Western U.S. region are input as the dependent variable in the SWE-fusion system. 799 Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) sites and 131 California Department of Water Resources (CA-DWR) California Data Exchange Center (CDEC) are potentially available for each model run. In addition, the Community Collaborative Rain, Hail and Snow (CoCoRaHS, https://www.cocorahs.org/) network provides over 500 snow measurements across the modeling domain.

Maps and Tables by Region

Maps and tables for each of the five western regions (Figure 1b) are shown below. Note that the basin-wide averages may reflect variable conditions across the elevation bands; see banded-elevation tables (linked below). Basin-wide percent of average is calculated across all model pixels inside a given basin and base elevation. Basin base elevations vary anywhere between 2,000’ to 7,000’. Base elevations are dependent on long-term snow coverage. For example, a base elevation in the north could be lower as compared to a base elevation in the south.

Pacific Northwest

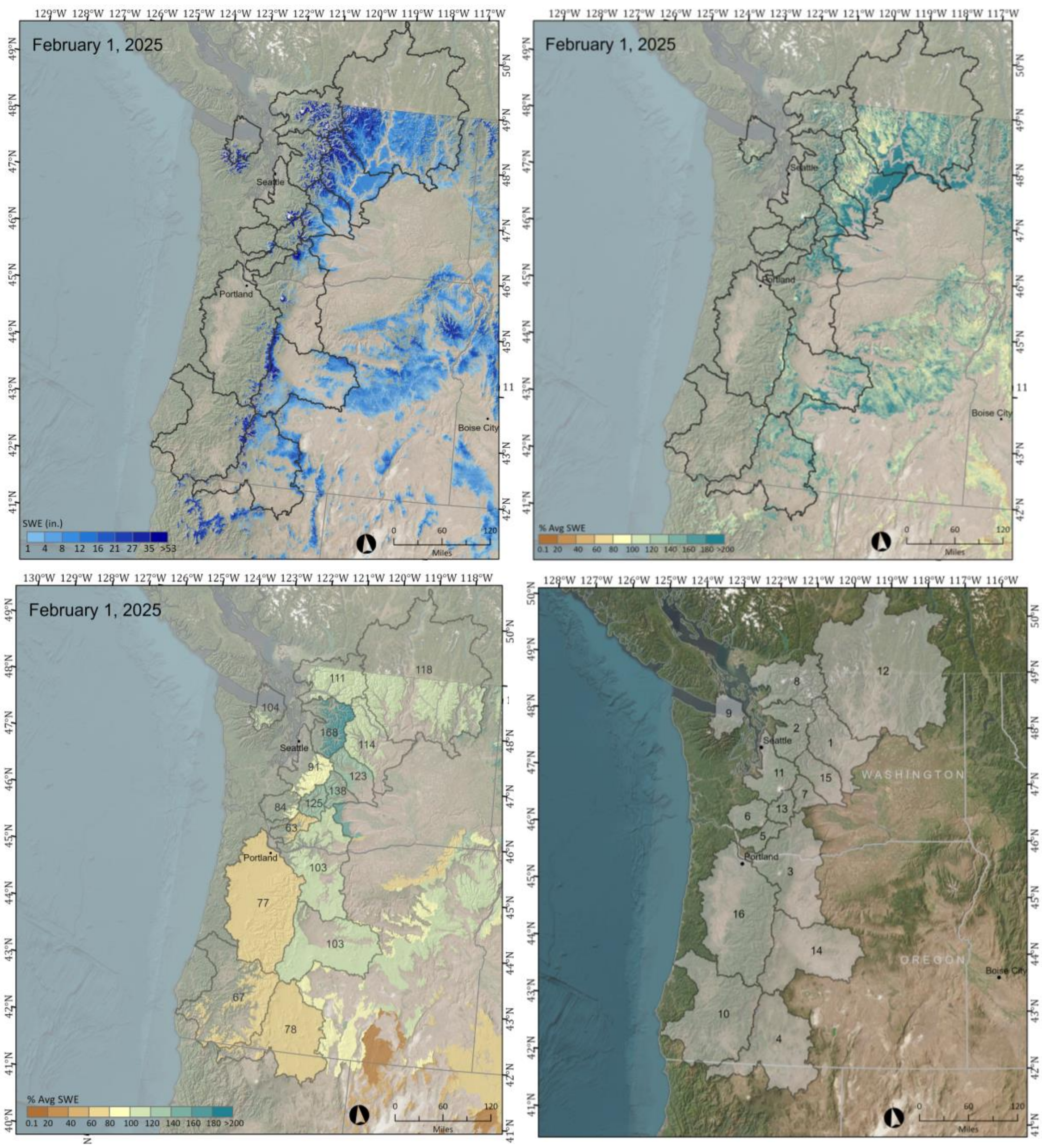

Figure 3. Estimated SWE and % of Average SWE across the Pacific Northwest Region. *SWE amounts (upper left), percent of long-term average (2001-2021) SWE calculated for each pixel (upper right), basin-wide percent of long-term average (lower left), and basin identification numbers that correspond to Table 1 below (lower right). The North Puget Sound and Upper Columbia basin portions that are inside Canada do not contain SWE-fusion model data due to lack of data availability needed to run the model in Canada.*

Table 1. SWE by watershed. Shown are percent of average SWE to date for the current date (2001-21 as derived from the regression model), mean SWE for the current report, current percent of snow-covered area, current SWE volume (acre-feet), the area (mi^2) inside each basin that contains data pixels (not including cloud-covered pixels, lakes or other satellite no data pixels), first of the month snow surveys, and current snow pillow sensors (the number of stations are in parentheses), for those areas collected, summarized for each basin. <u>*SWE tables by banded elevation are available below.*</u>

Pacific Northwest SWE Report for 2/1/2025

	% of Average	SWE (in)				Pillows	Surveys
Basin	2/1	2/1	SCA	Vol. (AF)	Area (mi. sq)	2/1	2/1
1. Central Columbia	114	13.8	76.4	1,568,056	2135.53	14.8 (7)	NA
2. Central Puget Sound	168	8.1	39.7	537,322	1238.13	18.4 (4)	NA
3. Hood-Sandy-Lower Deschutes	103	2.0	14.0	538,372	5079.56	12.5 (10)	NA
4. Klamath	78	3.1	26.6	1,197,545	7199.26	11.9 (15)	2.2 (1)
5. Lewis	63	1.5	7.6	47,593	580.6	21.8 (7)	NA
6. Lower Cowlitz	84	4.4	28.4	43,563	185.23	14.2 (2)	NA
7. Naches	138	8.3	53.6	271,134	610.43	25.4 (4)	NA
8. North Puget Sound	111	6.4	32.6	788,553	2312.56	22.1 (8)	NA
9. Olympic	104	13.4	52.2	169,952	237.74	17.3 (3)	NA
10. Rogue-Umpqua	67	2.0	9.2	353,038	3370.86	8.8 (6)	3.7 (9)
11. South Puget Sound	91	3.1	13.8	187,596	1147.98	13.3 (13)	NA
12. Upper Columbia	118	10.1	74.2	2,967,979	5501.67	11.3 (7)	NA
13. Upper Cowlitz	125	4.9	20.5	187,659	713.52	23.8 (3)	NA
14. Upper Deschutes-Crooked	103	4.7	43.5	1,394,183	5608.33	19.7 (7)	14.0 (6)
15. Upper Yakima	123	9.5	65.5	524,956	1033.4	15.4 (3)	NA
16. Willamette	77	0.7	3.7	429,973	11356.23	8.6 (18)	NA

*Basin boundaries were derived from a combination of NRCS basins and HUC8 boundaries.

North Continental

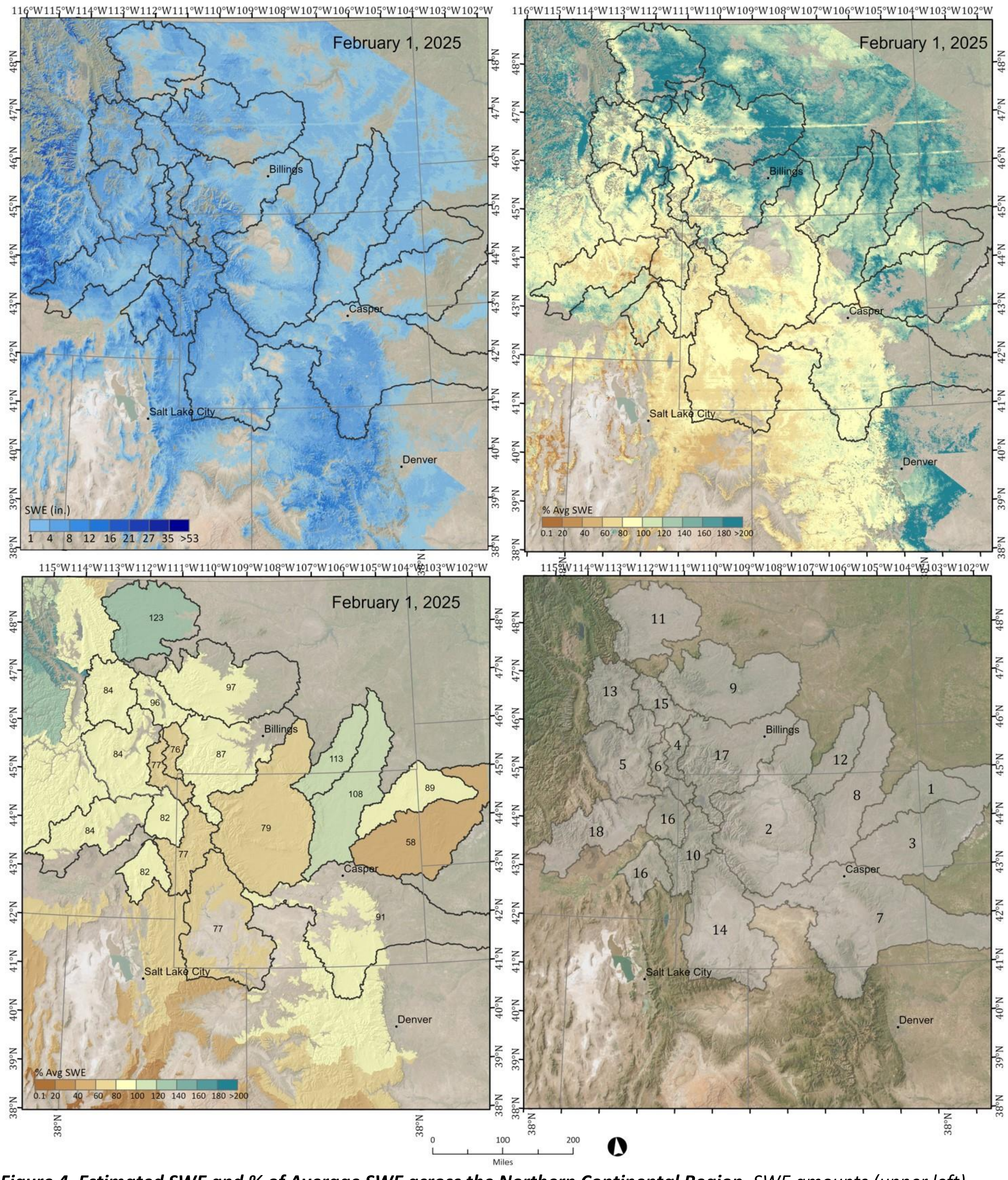

Figure 4. Estimated SWE and % of Average SWE across the Northern Continental Region. *SWE amounts (upper left), percent of long-term average (2001-2021) SWE calculated for each pixel (upper right), basin-wide percent of long-term average (lower left), and basin identification numbers that correspond to Table 2 below (lower right).*

Table 2. SWE by watershed. Shown are percent of average SWE to date for the current date (2001-21 as derived from the regression model), mean SWE for the current report, current percent of snow-covered area, current SWE volume (acre-feet), the area (mi^2) inside each basin that contains data pixels (not including cloud-covered pixels, lakes or other satellite no data pixels), first of the month snow surveys, and current snow pillow sensors (the number of stations are in parentheses), for those areas collected, summarized for each basin. <u>*SWE tables by banded elevation are available below.*</u>

North Continental SWE Report for 2/1/2025

	% of Average	SWE (in)				Pillows	Surveys
Basin	2/1	2/1	SCA	Vol. (AF)	Area (mi. sq)	2/1	2/1
1. Belle Fourche	89	1.7	48.5	667,741	7199.94	4.6 (1)	5.0 (4)
2. Bighorn	79	2.8	59.8	3,399,768	22739.68	5.8 (21)	4.5 (10)
3. Cheyenne	58	0.6	17.1	465,804	15348.24	4.2 (2)	2.6 (3)
4. Gallatin	76	4.3	65.6	419,646	1846.34	12.1 (4)	7.0 (1)
5. Jefferson	84	4.7	66.7	2,217,963	8787.88	6.4 (12)	4.8 (3)
6. Madison Headwaters in WY	77	4.6	65.9	615,696	2523.76	9.3 (7)	4.7 (1)
7. North Platte	91	6.0	86.7	3,282,975	10281.32	10.2 (22)	5.5 (1)
8. Powder	108	2.5	66.9	1,754,134	13384.71	4.3 (5)	1.8 (2)
9. Smith-Judith-Musselshell	97	3.8	62.3	1,679,367	8335.17	9.9 (8)	3.3 (1)
10. Snake	77	6.8	84.2	2,031,516	5626.28	10.4 (11)	NA
11. Sun-Teton-Marias	123	2.8	45.6	1,583,823	10463.47	3.9 (5)	5.0 (1)
12. Tongue	113	3.0	77.9	864,816	5399.93	5.6 (6)	6.6 (3)
13. Upper Clark Fork	84	4.1	58.7	1,318,139	5981.49	6.2 (12)	5.4 (9)
14. Upper Green	77	5.3	82.9	2,697,155	9539.23	7.4 (21)	NA
15. Upper Missouri	96	4.1	72.4	649,732	2950.79	4.4 (2)	3.4 (3)
16. Upper Snake Basins	82	5.5	84.6	2,013,179	6875.03	11.2 (10)	10.3 (9)
17. Upper Yellowstone	87	3.9	60.8	2,298,668	11070.32	8.0 (20)	5.6 (1)
18. Wood and Lost Basins	84	5.5	81.6	2,193,315	7420.11	7.1 (15)	8.1 (1)

*Basin boundaries were derived from a combination of NRCS basins and HUC8 boundaries.

South Continental

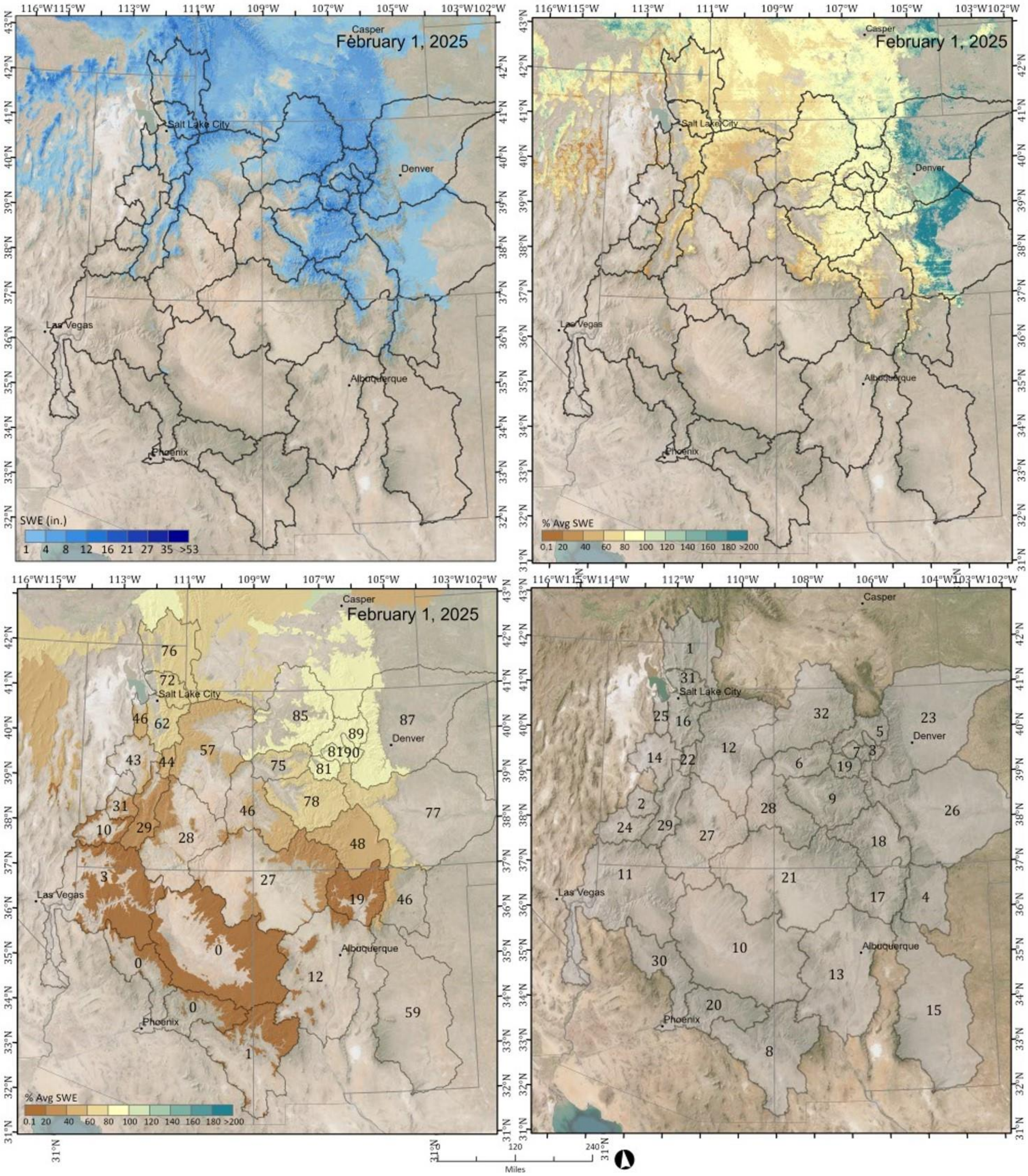

Figure 5. Estimated SWE and % of Average SWE across the Southern Continental Region. SWE amounts (upper left), percent of long-term average (2001-2021) SWE calculated for each pixel (upper right), basin-wide percent of long-term average (lower left), and basin identification numbers that correspond to Table 3 below (lower right).

Table 3. SWE by watershed. Shown are percent of average SWE to date for the current date (2001-21 as derived from the regression model), mean SWE for the current report, current percent of snow-covered area, current SWE volume (acre-feet), the area (mi^2) inside each basin that contains data pixels (not including cloud-covered pixels, lakes or other satellite no data pixels), first of the month snow surveys, and current snow pillow sensors (the number of stations are in parentheses), for those areas collected, summarized for each basin. *SWE tables by banded elevation are available below.*

South Continental SWE Report for 2/1/2025

	% of Average	SWE (in)				Pillows	Surveys
Basin	2/1	2/1	SCA	Vol. (AF)	Area (mi. sq)	2/1	2/1
1. Bear	76	5.5	84.3	1,817,889	6180.63	8.6 (18)	7.3 (2)
2. Beaver	31	0.6	10.7	26,857	835.62	6.4 (2)	NA
3. Blue	90	7.1	80.6	254,860	670.08	10.3 (5)	NA
4. Canadian	46	1.5	41.3	100,091	1264.58	3.7 (1)	NA
5. Colorado Headwaters	89	6.6	79.0	1,008,565	2874.24	9.1 (13)	NA
6. Colorado Headwaters-Plateau	75	4.6	57.1	446,370	1801.36	7.3 (1)	NA
7. Eagle	81	5.9	66.6	287,541	920.95	8.2 (3)	NA
8. Gila	1	0.0	0.4	1,983	4924.15	0.4 (5)	NA
9. Gunnison	78	5.4	72.9	1,867,919	6433.23	7.7 (11)	NA
10. Little Colorado	0	0.0	0.3	3,435	16378.65	1.4 (5)	0.4 (4)
11. Lower Colorado Mainstream	3	0.0	0.5	7,887	10694.84	1.7 (5)	0.2 (2)
12. Lower Green	57	3.7	58.9	1,126,327	5646.94	5.6 (24)	NA
13. Lower Rio Grande	12	0.2	5.8	23,424	1795.09	1.9 (4)	NA
14. Lower Sevier	43	1.3	26.4	64,438	897.01	5.1 (3)	NA
15. Pecos	59	2.2	41.3	39,704	331.18	2.7 (2)	NA
16. Provo-Utah Lake-Jordan	62	4.0	65.7	578,206	2681.09	9.4 (13)	10.5 (1)
17. Rio Chama-Upper Rio Grande	19	0.7	14.8	207,835	5206.68	3.1 (13)	NA
18. Rio Grande Headwaters	48	2.2	37.6	874,440	7595.21	5.6 (14)	NA
19. Roaring Fork	81	6.8	73.9	492,776	1359.47	8.9 (7)	NA
20. Salt	0	0.0	0.1	330	2361.01	0.4 (8)	NA
21. San Juan	27	1.3	19.4	445,105	6406.01	6.0 (15)	NA
22. San Pitch	44	2.3	37.0	107,401	857.15	7.7 (6)	5.7 (1)
23. South Platte	87	3.8	59.4	1,147,669	5619.72	8.0 (21)	6.8 (1)
24. Southwestern Utah	10	0.2	4.5	12,403	1439.87	1.9 (5)	NA
25. Toole Valley-Vernon Creek	46	1.3	40.4	65,010	906.18	7.0 (4)	NA
26. Upper Arkansas	77	2.9	55.2	922,491	5874.74	5.6 (7)	NA
27. Upper Colorado-Dirty Devil	28	1.1	20.4	153,825	2597.12	3.1 (7)	NA
28. Upper Colorado-Dolores	46	2.4	42.7	440,936	3434.19	6.5 (7)	3.6 (1)
29. Upper Sevier	29	1.1	23.9	227,705	3757.64	3.7 (15)	3.4 (1)
30. Verde	0	0.0	0.3	601	1816.32	0.5 (7)	NA
31. Weber-Ogden	72	5.5	83.3	600,773	2040.55	9.0 (16)	NA
32. White-Yampa	85	6.2	78.2	1,981,290	5948.29	11.1 (14)	NA

*Basin boundaries were derived from a combination of NRCS basins and HUC8 boundaries.

Intermountain

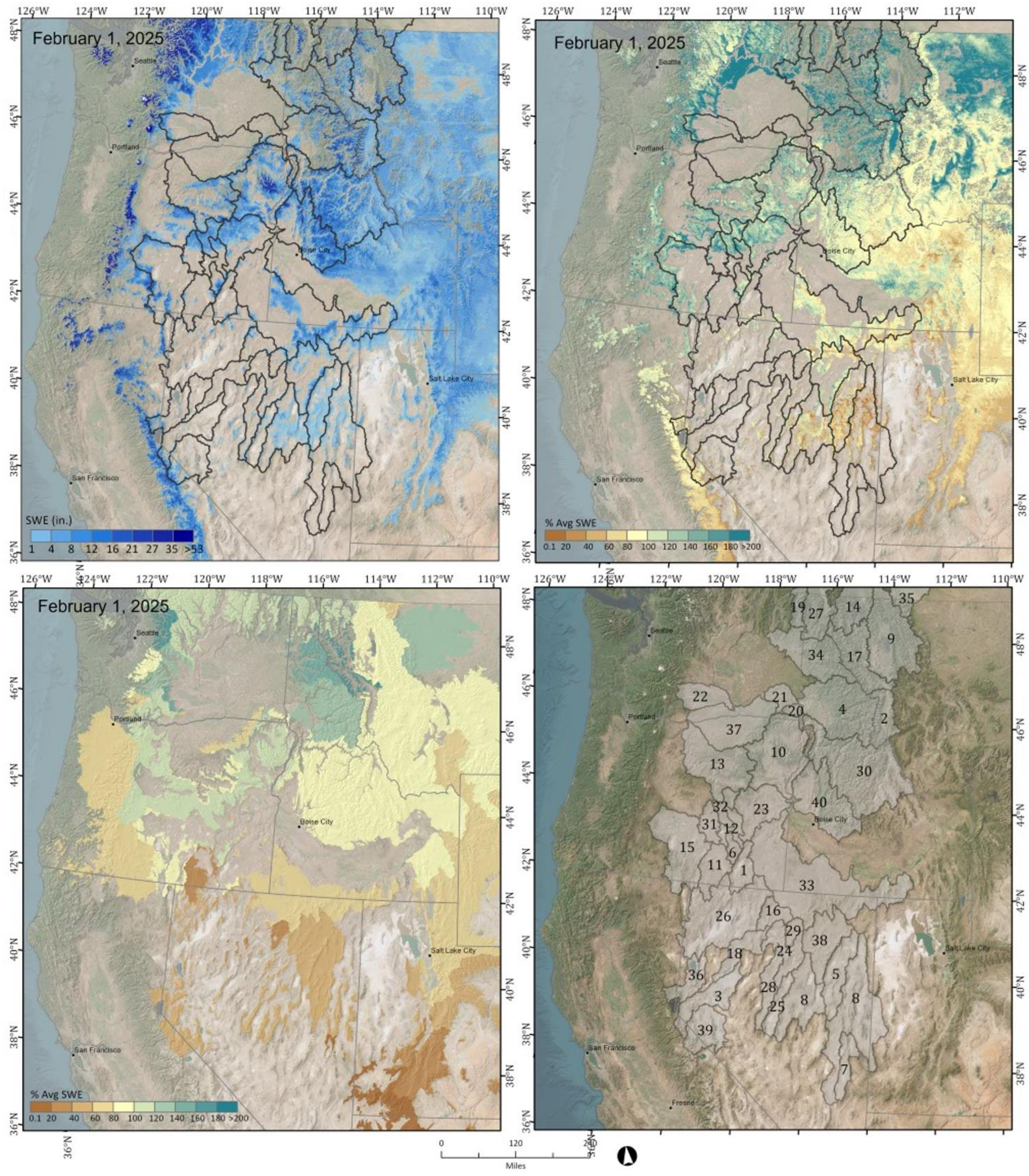

Figure 6. Estimated SWE and % of Average SWE across the Intermountain West Region. SWE amounts (upper left), percent of long-term average (2001-2021) SWE calculated for each pixel (upper right), basin-wide percent of long-term average (lower left), and basin identification numbers that correspond to Table 4 below (lower right).

Table 4. SWE by watershed. Shown are percent of average SWE to date for the current date (2001-21 as derived from the regression model), mean SWE for the current report, current percent of snow-covered area, current SWE volume (acre-feet), the area (mi^2) inside each basin that contains data pixels (not including cloud-covered pixels, lakes or other satellite no data pixels), first of the month snow surveys, and current snow pillow sensors (the number of stations are in parentheses), for those areas collected, summarized for each basin. *SWE tables by banded elevation are available below.*

Intermountain SWE Report for 2/1/2025

	% of Average	SWE (in)				Pillows	Surveys
Basin	2/1	2/1	SCA	Vol. (AF)	Area (mi. sq)	2/1	2/1
1. Alvord Lake	86	4.6	49.2	79,065	324.04	NA	NA
2. Bitterroot	92	5.1	50.8	535,748	1952.23	11.9 (4)	3.2 (1)
3. Carson	52	2.0	20.8	153,075	1405.22	9.5 (6)	1.8 (1)
4. Clearwater Basin	129	4.5	38.4	1,815,115	7487.78	17.4 (11)	NA
5. Clover Valley and Franklin	47	1.2	44.8	265,311	4048.38	7.2 (2)	12.0 (1)
6. Donner und Blitzen	115	10.0	89.1	118,590	221.72	20.6 (2)	NA
7. Dry Lake Valley	11	0.2	4.8	2,597	288.61	NA	NA
8. Eastern Nevada	41	1.3	32.5	307,748	4372.41	4.0 (8)	6.6 (1)
9. Flathead	93	2.5	24.8	992,582	7526.0	13.5 (11)	9.6 (10)
10. Grande Ronde-Burnt-Powder_Imnaha	106	6.9	62.0	1,953,383	5311.51	13.0 (10)	9.7 (3)
11. Guano	36	0.7	9.2	77,258	2036.3	NA	NA
12. Harney-Malheur Lakes	100	4.7	55.0	69,445	276.35	NA	NA
13. John Day	95	5.5	51.2	441,268	1501.84	15.0 (2)	NA
14. Kootenai	110	2.8	22.4	249,885	1672.59	12.9 (5)	17.2 (1)
15. Lake County-Goose Lake	86	3.7	34.2	710,603	3602.24	12.0 (2)	11.4 (1)
16. Little Humboldt	78	3.3	38.2	72,986	419.02	7.8 (3)	NA
17. Lower Clark Fork	175	5.7	46.5	443,517	1465.35	22.0 (3)	18.3 (2)
18. Lower Humboldt	34	1.0	13.3	13,908	274.23	4.1 (1)	NA
19. Lower Pend Oreille	131	8.3	52.9	57,380	128.96	17.5 (1)	NA
20. Lower Snake-Asotin	89	2.8	30.5	48,302	328.28	4.0 (2)	NA

*Basin boundaries were derived from a combination of NRCS basins and HUC8 boundaries.

Intermountain SWE Report for 2/1/2025							
	% of Average	SWE (in)				Pillows	Surveys
Basin	2/1	2/1	SCA	Vol. (AF)	Area (mi. sq)	2/1	2/1
21. Lower Snake-Tucannon	127	6.7	67.9	39,318	109.27	NA	NA
22. Lower Yakima	144	6.6	59.3	171,051	489.29	16.1 (2)	NA
23. Malheur	115	7.3	76.0	384,164	992.38	11.1 (3)	NA
24. Middle Humboldt	56	1.5	25.1	50,939	633.11	NA	8.7 (1)
25. Northern Big Smoky Valley	54	1.8	28.8	54,196	569.69	NA	NA
26. Northern Great Basin	46	1.5	18.0	173,030	2226.46	4.6 (2)	NA
27. Panhandle Basins	116	3.4	23.7	296,741	1643.54	19.1 (3)	NA
28. Reese	58	2.1	30.6	54,028	491.03	7.9 (2)	NA
29. Rock	35	0.8	11.2	35,627	834.56	8.4 (1)	2.1 (1)
30. Salmon Basin	94	7.2	72.7	4,574,361	11931.81	11.3 (11)	NA
31. Silver	103	4.8	49.8	110,447	431.37	NA	NA
32. Silvies	119	6.2	74.1	432,133	1315.64	10.0 (2)	NA
33. Southern Snake Basins	67	2.9	41.2	1,919,321	12499.77	7.4 (13)	5.0 (5)
34. Spokane	152	3.4	29.1	574,052	3145.86	12.2 (8)	NA
35. St. Mary	79	4.0	47.8	136,724	647.78	4.6 (1)	NA
36. Truckee	49	2.2	19.7	165,931	1419.5	9.7 (9)	NA
37. Umatilla-Walla Walla-Willow	69	1.8	16.5	137,094	1433.69	12.3 (7)	NA
38. Upper Humboldt	55	1.9	30.8	511,382	5032.36	7.1 (7)	6.0 (8)
39. Walker	51	1.8	26.0	183,967	1938.91	8.7 (6)	NA
40. West Central Basins	94	8.9	77.9	2,656,094	5619.91	15.9 (13)	NA

*Basin boundaries were derived from a combination of NRCS basins and HUC8 boundaries.

Sierra Nevada

There is a separate SWE report that has a stronger focus on the Sierra Nevada available **here**. This report takes additional vetting measures and bias corrects with Airborne Snow Observatory data. Below is a sample of the maps provided in this report.

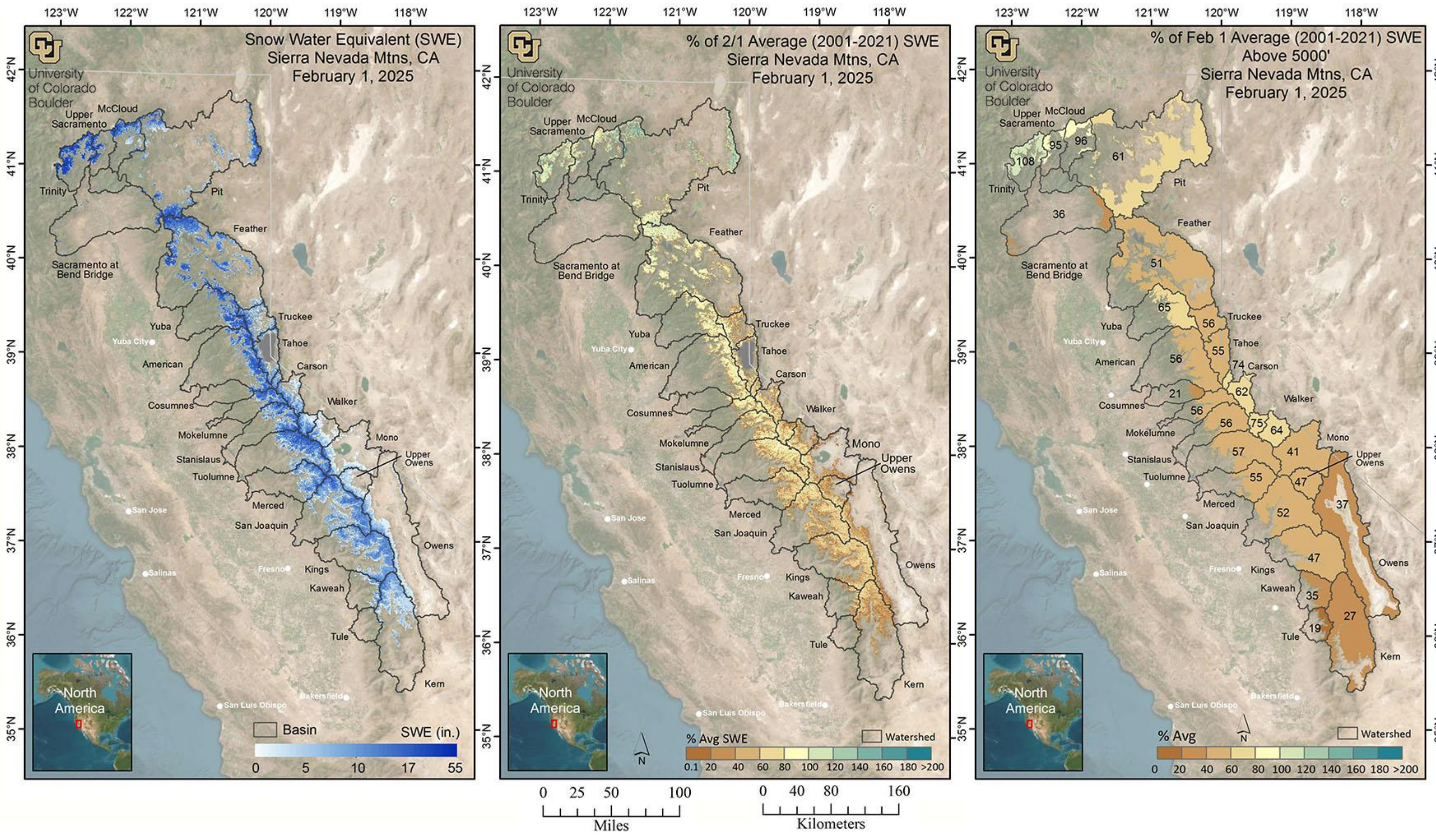

Figure 7. Estimated SWE and % of Average SWE across the Sierra Nevada. SWE amounts (left), and percent of average (2001-2021) SWE for the Sierra Nevada, calculated for each pixel (middle) and basin-wide (right). Basin-wide percent of average is calculated across all model pixels >5000' elevation.

Table 5. SWE by watershed. Shown are percent of average SWE to date for the current date (2001-21 as derived from the regression model), mean SWE for the current report, current percent of snow-covered area, current SWE volume (acre-feet), the area (mi^2) inside each basin that contains data pixels (not including cloud-covered pixels, lakes or other satellite no data pixels), first of the month snow surveys, and current snow pillow sensors (the number of stations are in parentheses), for those areas collected, summarized for each basin.

Sierra Nevada SWE Report for 2/1/2025

	% of Average	SWE (in)				Pillows	Surveys	
Basin	2/1	2/1	SCA	Vol. (AF)	Area (mi. sq)	2/1	2/1	SNODAS* (in)
Trinity	108	14.9	79.7	255,560	321.3	22.1 (4)	18.5 (1)	21.9
Upper Sacramento	95	12.4	69.8	76,093	115.2	21.3 (2)	24.3 (3)	18.4
McCloud	96	10.8	69.9	94,974	164.9	18.3 (1)	18.5 (1)	20.5
Pit	60	3.2	25.0	347,481	2064.7	13.0 (7)	7.5 (2)	4.4
Sacramento at Bend Bridge	36	3.0	18.6	38,511	239.8	NA	0.0 (1)	7.2
Feather	51	4.9	36.8	546,712	2086.7	17.6 (5)	11.7 (18)	8.6
Yuba	65	7.8	53.3	215,398	515.6	25.0 (5)	18.1 (12)	15.6
American	56	6.8	48.8	287,387	794.9	11.4 (10)	9.9 (15)	9.5
Cosumnes	20	1.6	12.5	7,801	91.9	NA	NA	3.0
Mokelumne	56	6.7	47.8	112,784	314.8	14.6 (3)	10.2 (9)	8.1
Stanislaus	55	6.3	46.8	186,170	557.0	12.1 (5)	9.5 (14)	6.4
Tuolomne	57	6.8	50.6	329,502	909.8	11.1 (7)	8.9 (12)	7.0
Merced	54	5.9	49.3	169,453	538.8	11.6 (2)	9.4 (6)	6.6
San Joaquin	52	6.1	56.5	394,697	1207.1	5.2 (7)	9.9 (16)	5.8
Kings	46	5.6	53.7	358,754	1207.0	8.8 (6)	8.2 (20)	5.5
Kaweah §	35	2.6	30.1	43,310	314.1	NA	4.8 (2)	3.9
Tule	18	0.7	9.0	5,402	137.6	NA	NA	0.8
Kern	27	2.2	27.0	197,492	1682.0	6.0 (5)	5.9 (13)	1.7
Truckee	56	5.8	47.7	126,469	411.5	10.6 (6)	19.4 (1)	9.4
Tahoe	55	6.3	50.8	101,713	304.9	10.0 (7)	6.3 (5)	7.6
W Carson	73	8.9	72.8	30,808	65.0	10.2 (3)	12.0 (1)	9.1
E Carson	61	5.3	51.3	100,009	354.3	8.9 (3)	NA	5.4
W Walker	74	8.2	76.9	78,806	179.6	11.5 (3)	6.0 (2)	7.9
E Walker	63	3.2	46.8	59,711	350.7	6.2 (1)	5.9 (1)	2.8
Mono	40	1.4	27.6	72,754	1002.9	NA	9.4 (4)	1.0
Upper Owens	46	2.9	42.6	58,420	373.7	12.8 (1)	12.7 (3)	2.3
Owens	37	1.3	25.7	123,384	1772.0	6.5 (4)	6.5 (7)	0.9

§ Data in all ASO-collected basins have been bias-corrected using ASO data and therefore the SWE changes might not represent snowmelt/accumulation but rather an update to the SWE estimates based on airborne data.

† Deep and recent snow in areas that typically are snow-free can report high percent of average for this date because the mean 2001-2021 regression-derived SWE for that area is low or 0.

‡ For volume totals above Shasta Lake add Upper Sac, McCloud and Pit volumes. For volume totals above Bend Bridge add Upper Sac, McCloud, Pit and Sac at Bend Bridge volumes.

* This is a comparison to the SNODAS (SNOw Data Assimilation System) nationwide product from the National Weather Service.

Elevation Banded SWE Tables:

Due to the length of the banded elevation tables (tables 6-10), that data is being hosted on our GitHub repository. Direct links to all of the tables are below. Access to the GitHub repository for the tables in both HTML and CSV formats is **here**.

- Pacific Northwest
- North Continental
- South Continental
- Intermountain, part 1
- Intermountain, part 2
- Sierra Nevada

The value of spatially explicit estimates of SWE

Snowmelt makes up the large majority (~60-85%) of the annual streamflow in the Western U.S. The spatial distribution of 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 vary a lot from year to year, influencing the magnitude and timing of snowmelt-driven runoff.

SWE is operationally monitored at hundreds of NRCS SNOTEL and California DWR CDEC snow pillow sites spread across the Western U.S., providing a critical first-order snapshot of conditions, and the basis for runoff forecasts from the CA DWR, NRCS and NOAA. However, conditions at snow pillow 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 pillow sites. The spatial SWE-fusion creates a detailed picture of the spatial pattern of SWE using snow pillows, satellite, and other data, extending beyond the snow pillow sites to unmonitored areas.

Interpreting the spatial SWE estimates in the context of snow pillow sites

The spatial SWE-fusion product estimates SWE for every pixel where the fractional snow-covered area (fSCA) satellite product identifies snow-cover. Comparatively, snow pillow samples on average 8-20 points per basin within a narrower elevation range. Thus, the basin-wide percent of long-term average from the spatial SWE-fusion estimates is not directly comparable with the snow pillow basin-wide percent of average. A better comparison might be made with the % average in the elevation bands (elevation-banded tables 6-10) that contain snow pillow sites.

Location of Reports, Excel Format Tables, and JPG Maps

https://github.com/CU-Mountain-Hydrology/WestWide

Methods

The spatial SWE-fusion estimation method is described in Yang, et. al. (2022) and Schneider and Molotch (2016). The method uses a General Linear Model in which the dependent variable is derived from the operationally measured in situ SWE from all online NRCS SNOTEL and CDEC snow pillow sites in the domain and when applicable the CoCoRaHS SWE values. The snow pillow SWE observations are scaled by the satellite-based fractional snow-covered area (fSCA) across the 500 meter pixel containing that snow pillow site before being used in the linear regression model. The fSCA is a near-real-time cloud-free daily satellite image from the Snow Today fSCA image (Rittger, et. al. 2019, https://nsidc.org/snow-today) which uses the SPIReS algorithm (Bair, et al. 2021).

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

- Physiographic variables that affect snow accumulation, melt, and redistribution, including elevation, latitude, upwind mountain barriers, slope, and others. See Table 1 in Yang, et. al., (2022) for the full set of these variables.
- The historical daily SWE pattern (1985-2021) retrospectively generated using historical Landsat 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 Fang, et. al., (2022) for details. (For computational efficiency, only one image during the 1985-2021 period that best matches the real-time snow pillow-observed pattern is selected as an independent variable.)
- Satellite-observed daily mean fractional snow-covered area (DMFSCA) derived from Rittger, et. al., (2019) data.

The real-time regression model for this date has been validated by cross-validation, whereby 10% of the snow pillow data are randomly removed and the model prediction is compared to the measured value at the removed snow pillow stations. This is repeated 30 times to obtain an average R-squared value, which denotes how closely the model fits the snow pillow data. During development of this regression method, the model was also validated against independent historical SWE data from Airborne Snow Observatory lidar data and from snow surveys at 10 locations in Colorado.

List of All Known Data Issues/Caveats

- RECENT SNOWFALL – There are occasionally problems with lower-elevation SWE estimates due to recent snowfall events that result in extensive snow-cover extending to valley locations where measurements are not available. This scenario results in an over-estimation of lower- elevation SWE.
- LIMITED SNOW PILLOW DATA – When snow at the snow pillow sites melts out, but remains at higher elevations, the model tends to overestimate SWE at the under-monitored upper elevations. This issue typically occurs late in the melt season, resulting in less accurate SWE prediction at higher elevations compared to earlier in the snow season.
- CLOUD COVER – Cloud cover can obscure satellite measurements of snow-cover. While careful checks are made, occasionally the misclassification of clouds as snow or *vice versa* may result in the mischaracterization of SWE or bare-ground.
- LOW LOOK ANGLE – When a satellite does not pass directly over a region but the area is still included within the satellite sensor's field of view, this is referred to as a low "look angle". The resulting image has lower effective resolution – this "blurry" MODSCAG data still contains useful information but may lead to overestimation of SWE near the margins of the snow-cover extent.
- POOR QUALITY SNOW SENSOR DATA – Although data QA/QC is performed, occasional SNOTEL sensor malfunction may result in localized SWE errors.
- ANOMALOUS SNOW PATTERNS – Anomalous snow years or snow distributions may cause SWE error due to the model design to search for similar SWE distributions from previous years. If no close seasonal analogue exists, the model is forced to find the most similar year, which may result in error.
- DENSE FOREST COVER – Dense forest cover at lower elevations where snow-cover is discontinuous can cause the satellite to underestimate the snow-cover extent, leading to underestimation of SWE.
- PERCENT OF AVERAGE CALCULATIONS - Data utilized to generate this report change to optimize model performance. To maintain consistency across the historical record, the percent of average values are based on our baseline algorithm and therefore there can be discrepancies between absolute SWE values and corresponding percent of averages.
- MODELING METHODS - We work to generate the best SWE estimates for each reporting date. Our methods can change from one report to another. Sometimes data changes between reports is an artifact of method changes.
- EARLY SEASON FSCA ERRORS – The gap-filled fSCA requires some cloud-free images to determine fSCA amounts. Early in the season and if it has been particularly cloudy the algorithm hasn't had time to calculate fSCA amounts in some areas, typically in the Pacific Northwest and northern areas of the domain.

References and Additional Sources

Bair, E.H., T. Stillinger and J. Dozier (2021). Snow Property Inversion From Remote Sensing (SPIReS): A Generalized Multispectral Unmixing Approach With Examples From MODIS and Landsat 8 OLI. IEEE Transactions on Geoscience and Remote Sensing, 59(9): 7270-7284. DOI: 10.1109/TGRS.2020.3040328.

Commission for Environmental Cooperation (2009). Ecological regions of North America, Level 3, scale 1:4,000,000, Commission for Environmental Cooperation, Montreal, Quebec, Canada.

Hall, D. K. and G. A. Riggs (2021). MODIS/Terra Snow Cover Daily L3 Global 500m SIN Grid, Version 61. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/MODIS/MOD10A1.061. Date Accessed May 10, 2022.

Fang, Y., Liu, Y. & Margulis, S.A. A western United States snow reanalysis dataset over the Landsat era from water years 1985 to 2021 (2022). Sci Data 9, 677. https://doi.org/10.1038/s41597-022-01768-7.

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.

Rittger, K., M. S. Raleigh, J. Dozier, A. F. Hill, J. A. Lutz, and T. H. Painter (2019). Canopy Adjustment and Improved Cloud Detection for Remotely Sensed Snow Cover Mapping. Water Resources Research 24 August 2019. doi:10.1029/2019WR024914.

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.

Trujillo, E., and N. P. Molotch (2014). Snowpack regimes of the Western United States, Water Resour. Res., 50, 5611–5623, doi:10.1002/ 2013WR014753.

Yang, K., K. N. Musselman, K. Rittger, S. A. Margulis, T. H. Painter and N. P. Molotch (2022). Combining ground-based and remotely sensed snow data in a linear regression model for real-time estimation of snow water equivalent. *Advances in Water Resources,* 160, 2022, 104075. DOI: 10.1016/j.advwatres.2021.104075.