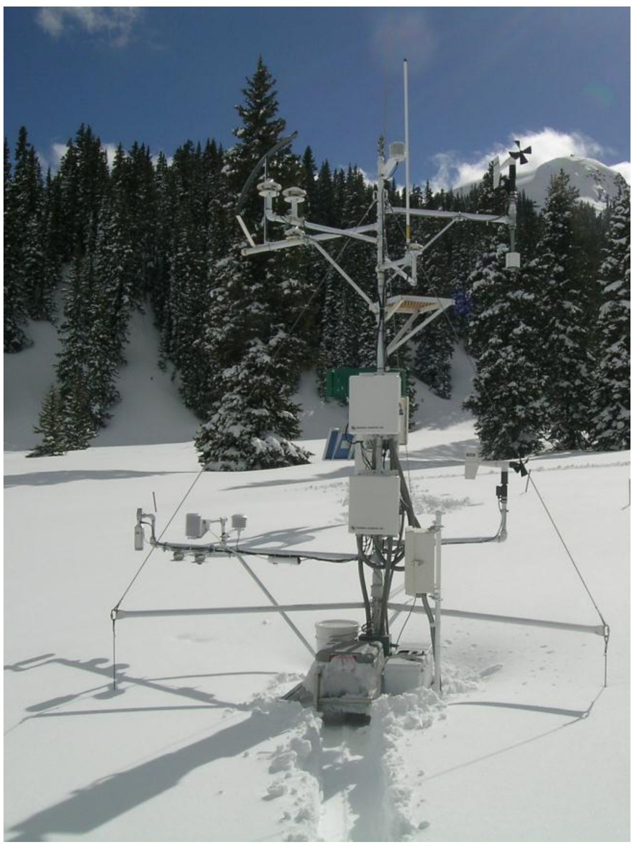
Colorado Dust-on-Snow (CODOS)

Water Year 2012 Summary Report



May 11, 2011 May 12, 2012

Swamp Angel Study Plot in Senator Beck Basin Study Area near Red Mountain Pass

A Case Study in Interannual Variability of Colorado Snowpack and the Role of Desert Dust

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CENTER FOR SNOW & AVALANCHE STUDIES

WATER YEAR 2012
COLORADO DUST ON SNOW (CODOS) SUMMARY REPORT

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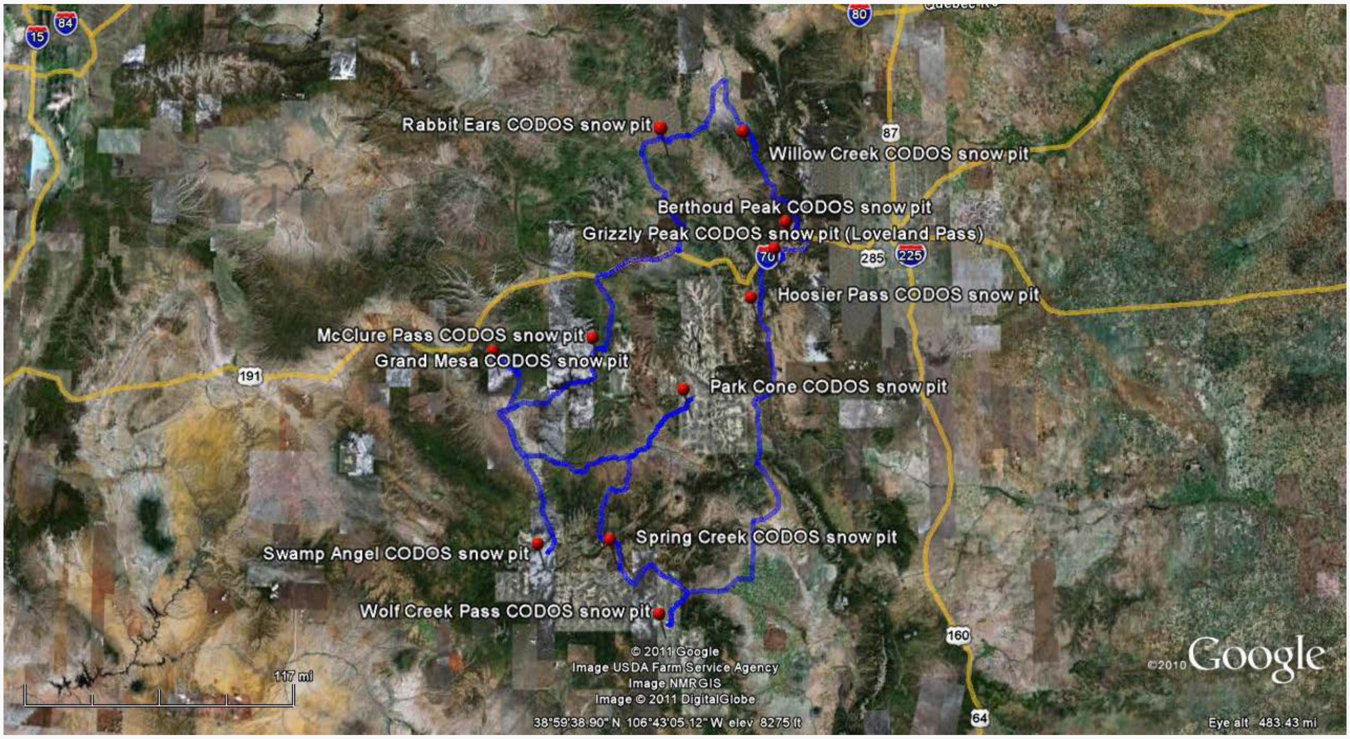
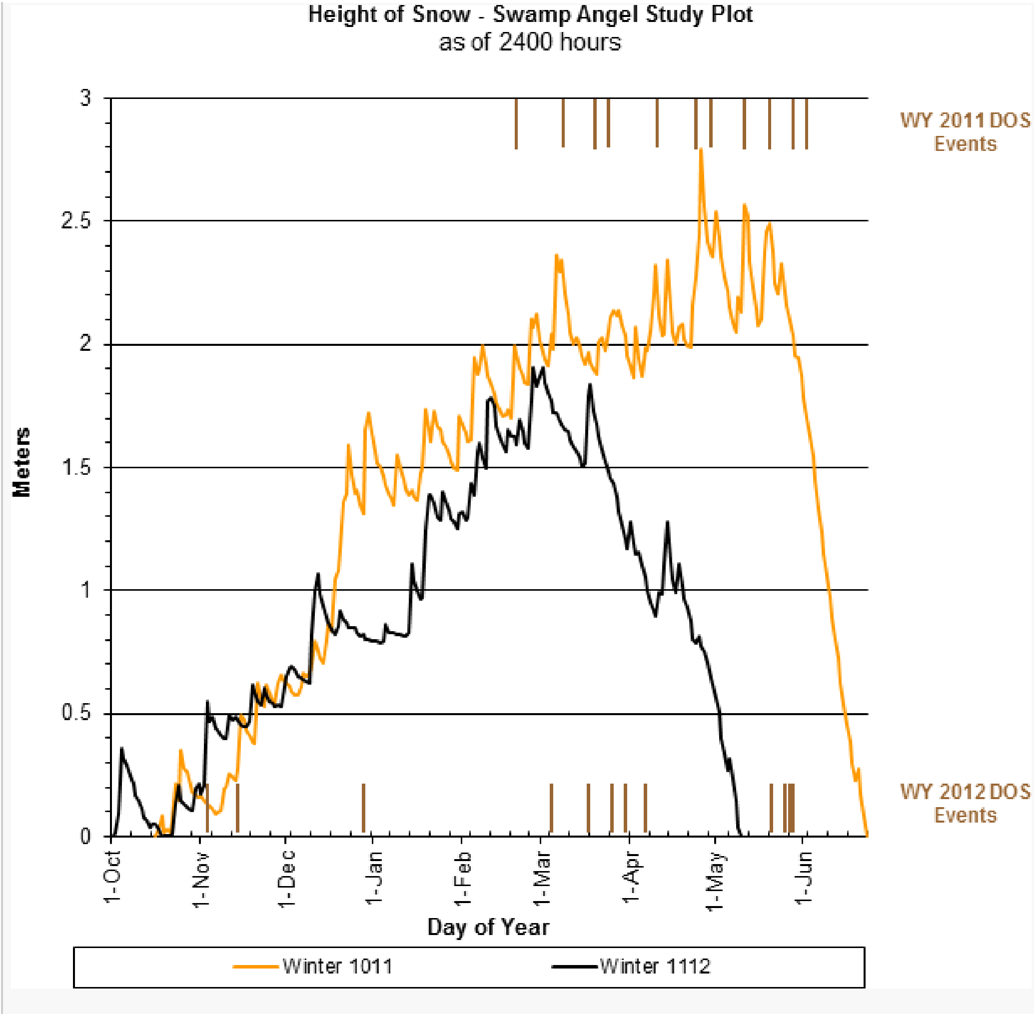
2012 CODOS SUMMARY



Water Years 2011 and 2012 have provided a case study in interannual variability of Colorado snowpack formation and ablation. Although both winters were under La Niña influence, dramatically different late-winter and spring conditions produced diametrically opposing snowmelt scenarios, perhaps representing seasonal extremes. Unrelenting storms in Mar/Apr/May 2011 produced very large or record snowpacks and very late dates of peak SWE. Snowmelt began late but, enhanced by early June temperatures and considerable dust-in-snow, rapidly attained and sustained high rates and record or near-record streamflows ensued.

In sharp contrast, extremely dry Mar/Apr/May weather in 2012 resulted in low or very low values of peak SWE, very early in the spring. Prolonged periods of dust-on-snow exposure at the snowpack surface, along with dry, sunny, and sometimes unseasonably warm weather beginning in early March, enabled snowpack ablation to begin early. Snowmelt proceeded in a notably synchronized pattern throughout the Colorado mountains, with early and high initial levels of runoff in March and early April, to sub-par peak discharge levels, followed by very steep declines in runoff to extremely low flows in late June.



Despite vastly different Mar/Apr/May precipitation regimes, Water Years 2011 and 2012 produced much smaller differences in spring dust-on-snow conditions, with WY 2012 coming close to matching WY2011 at the Senator Beck Basin Study Area, our baseline monitoring site. We observed 12 dust-on-snow events in WY 2012 at our Swamp Angel Study Plot, compared to 11 events in WY 2011 (see graph above showing dust events for past two years as brown bars), but the total mass of dust deposited was somewhat lower in 2012 than in 2011. Given the very early ablation of snowcover statewide, several dust events in May 2012 may have fallen without effect onto mostly bare ground, rather than snow, as was the case at SASP. However, even the final event, D12 on May 26th, found some lingering alpine snow cover and further reduced snow albedo, in Senator Beck Basin and elsewhere in the state.

Dust-on-Snow Events Documented per Month, by Winter

Senator Beck Basin Study Area at Red Mountain Pass – San Juan Mountains

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	**Total**
2002/2003					2		1			**3**
2003/2004							2	1		**3**
2004/2005	0	0	0	0	0	1	2	1	0	**4**
2005/2006	0	0	1	0	1	1	3	2	0	**8**
2006/2007	0	0	1	0	1	1	3	1	1	**8**
2007/2008	0	0	0	0	0	3	3	1	0	**7**
2008/2009	1	0	1	0	1	4	5	0	0	**12**
2009/2010	1	0	0	0	0	1	4	3	0	**9**
2010/2011	0	0	0	0	1	3	3	4	0	**11**
2011/2012	0	2	1	0	0	3	2	4	0	**12**

2010/2011 (WY 2011): Feb 19, Mar 6, Mar 17, Mar 21, April 8, April 21, April 29, May 9, May 18, May 26, May 29
2011/2012 (WY2012): Nov 5, Nov 13, Dec 31, Mar 6, Mar 18, Mar 26, Apr 1, Apr 6, May 18, May 23, May 25, May 26
See the complete CODOS dust log for dust-on-snow dates during other years and links to windroses for each event.

Throughout the winter season, beginning with the first snowcover until “snow all gone” (SAG) in the spring, CSAS/CODOS collects, as feasible, a time series of $0.5m^2$ samples of individual dust layers at Swamp Angel Study Plot. Samples are processed by USGS lab technicians with the Geology and Environmental Change Science Center conducting research on “effects of climatic variability and land use on American drylands”.

The total number of dust-on-snow events in WYs 2011 and 2012 (at 11 and 12 dust storms, respectively) and their season dust mass loading totals were notably similar, at 14 grams per square meter in WY2011 and an estimated 11-12 grams per square meter in WY 2012 (mass of the final four events was estimated, due to loss of snowcover at Swamp Angel Study Plot).

Swamp Angel Study Plot Dust Mass Loading Data - WY 2011
From 0.5m2 samples collected by CSAS, processed by USGS Denver

Dust Event	Date	Visually Estimated Organic Content	Gross Weight 0.5 m2 Sample (grams)	**Estimated Mass Loading Grams/m2**	Notes
D1	19-Feb-11	na	no sample	**na**	Extremely minor event
D2	6-Mar-11	na	no sample	**na**	Extremely minor event
D3	17-20-Mar-11	80%	0.1378	**0.276**	Discrete sample
D4	21-Mar-11	<10%	2.562	**5.124**	Merged sample; D4 value derived from a merged D3-D4 sample, less the D3 sample
D5	8-Apr-11	<10%	0.608	**1.216**	Discrete sample
D6	21-Apr-11	<10%	0.3355	**0.671**	Discrete sample
D7	29-Apr-11	20%	0.2391	**0.478**	Discrete sample
D8	9-May-11	<10%	0.5393	**1.079**	Discrete sample
D9	18-May-11	na	no sample	**na**	Minor dust-on-dust event; discrete sampling infeasible
D10	26-May-11	na	no sample	**na**	Minor dust-on-dust event; discrete sampling infeasible
D11	29-May-11	na	no sample	**na**	Major dust-on-dust event; discrete sampling infeasible
D2-D11 Merged	**6/14/11 Sample**	**20%**	**7.0646**	**14.129**	**Sample of top few cm after D11-D2 layers had merged; some 'seepage' missed**

Swamp Angel Study Plot Dust Mass Loading Data - WY 2012
From 0.5m2 samples collected by CSAS, processed by USGS Denver

Dust Event	Date	Visually Estimated Organic Content	Gross Weight 0.5 m2 Sample (grams)	**Estimated Mass Loading Grams/m2**	Notes
D1	November 5, 2011	<10%	0.2684	**0.537**	Discrete sample
D2	November 13, 2011	"lots"	0.4599	**0.920**	Discrete sample, 0.2931 grams of pine needles and seed pods removed before 'gross weight'
D3	December 31, 2011	"mostly"	0.0670	**0.134**	Discrete samples, lots of dark, large, dark (black) organic particles
D4	March 6, 2012	not char	0.1687	**0.337**	Discrete sample of typical brown dust; began dry on slick m/f crust overnight and w/snow next day
D5	March 18, 2012	not char	1.6387	**3.277**	Discrete sample of 'wet' event, 'iced tea' color
D6	March 26, 2012	na	na	**na**	Very minor dust-on-dust event at SBB; discrete sampling infeasible
D7	April 1, 2012	na	na	**na**	Dust-on-dust at SBB; discrete sampling infeasible
D8	April 6, 2012	na	na	**na**	Significant dust-on-dust at SBB; skiff new snow onto D8; discrete sampling infeasible
D9	May 18, 2012	na	na	**na**	Snow all gone at SASP - sampling infeasible, but was very minor dry event
D10	May 23, 2012	na	na	**na**	Snow all gone at SASP - sampling infeasible, but was very minor dry event
D11	May 25, 2012	na	na	**na**	Snow all gone at SASP - sampling infeasible, but was very minor dry event
D12	May 26, 2012	na	na	**na**	Snow all gone at SASP - sampling infeasible, but was major dry event, perhaps largest of season
D4-D8 merged	Sampled May 4	na	3.5336	**7.067**	Merged sample of D8-D4 collected May 4; some infiltration losses already incurred
Estimated D6,7,8				*3.4524*	*Inferred mass, by subtracting measured D4 and D5 events from merged D8-D4 sample*
Measured D1-D8				8.6578	Sum of discretely sampled D1, D2, D3, plus merged D4-D8 sample
Estimated D9-12				2.4 - 3.4	Range of plausible totals for D9-D12, predominately from event D12
Estimated D1-D12				**11 to 12**	**Estimated total mass loading, in grams per square meter**

The Center for Snow and Avalanche Studies conducted three CODOS field campaigns in spring 2012, visiting our ten additional CODOS monitoring sites in a 1,000+ mile circuit and issuing site-specific CODOS Updates on the go. Between circuits, CSAS issued a number of Dust Alerts, as new dust-on-snow events were observed at Senator Beck Basin. By our final field campaign in early May, many sites had already experienced SAG and the remaining sites were rapidly approaching SAG, pre-empting a fourth circuit.

CODOS and Other SNOTEL Sites - WY 2012 Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Post-Peak Added SWE	Adjusted Daily Mean Loss SWE	Maximum 5-Day Moving Average of Daily Loss of SWE	Period Mean Temp C	SBBSA DOS Post Peak SWE
Red Mtn Pass	3/23/2012	17.8	57	2.2	0.35	0.86	2.2	7
Slumgullion Pass	4/6/2012	12.1	43	2.0	0.33	1.22	3.1	4
Wolf Creek Summit	3/25/2012	24.8	63	4.1	0.46	1.56	4.7	7
Beartown	3/23/2012	17.1	38	1.8	0.50	1.30	1.1	7
Lizard Head	3/11/2012	11.3	50	2.7	0.28	0.56	1.8	8
Park Cone	3/27/2012	8.1	37	0.3	0.23	0.62	3.9	6
Schofield Pass	3/24/2012	21.9	47	2.8	0.53	1.14	2.8	7
McClure Pass	3/22/2012	12.7	32	1.7	0.45	1.06	6.1	7
Independence Pass	3/24/2012	9.9	38	0.3	0.27	0.82	1.6	7
Hoosier Pass	3/28/2012	10.2	48	2.9	0.27	0.9	2.4	6
Grizzly Peak	3/22/2012	11.9	44	2.6	0.33	0.76	2.4	7
Berthoud Summit	3/6/2012	13.0	60	3.2	0.27	1.14	1.4	8
Willow Creek Pass	3/8/2012	7.7	55	1.7	0.17	0.42	1.9	8
Rabbit Ears Pass	3/13/2012	15.2	57	4.4	0.34	0.82	4.1	8
Mesa Lakes	3/24/2012	12.7	43	2.1	0.34	0.98	3.4	7
Mean	03/21/12	13.8	47	2.3	0.34	0.94	2.9	6.9
Max	04/06/12	24.8	63	4.4	0.53	1.56	6.1	8
Min	03/06/12	7.7	32	0.3	0.17	0.42	1.1	4
Range	31	17.1	31	4.1	0.35	1.14	5.0	4

Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE
Non-CODOS SNOTEL sites shown in italics

Analysis of WY2012 melt rate data at fifteen Snotel sites, showing date and quantity of peak SWE, days from peak SWE to “snow all gone” (SAG), total additional precipitation after date of peak SWE, an adjusted mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG. The number of dust-on-snow events logged at the Senator Beck Basin after the date of peak SWE at a given Snotel site is shown in the last column.

The table above summarizes Snotel site data from ten CODOS sites and five additional locations, summarizing rates of snowmelt from spring 2006 to spring 2012, the period during which we’ve rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. Since the Snotel network is the only spatially extensive system continuously monitoring snowmelt throughout the Colorado mountains, year-to-year comparisons of Snotel melt rate data may yield insights into dust effects on local watershed-scale processes.

However, as we often note, each Snotel site has unique site characteristics. Many Snotel sites experience a radiative regime where surrounding trees reduce the access of direct, incoming solar radiation to the snowcover on the snow pillow, and where re-radiation of long wave energy from that vegetation, and reduced skyview, may inhibit radiant cooling and extend surface snowmelt during nighttime hours. As a consequence, many Snotel sites do not experience the maximum effects of dust reductions in snow albedo, and snowmelt forcing, that we observe at Senator Beck Basin study sites, where solar access is unimpeded. Among the Snotel sites we visit, the Berthoud Summit site most closely resembles the radiative regime at our subalpine Swamp Angel Study Plot in Senator Beck Basin.

Aggregated CODOS and Other SNOTEL Sites - Snowmelt Season Summary Data WY 2006 through WY 2012

15 total sites

	Group Mean Date Peak SWE	Group Mean Peak SWE	Group Mean Days to SAG	Group Mean Post-Peak Added SWE	Group Mean Adjusted Daily Mean Loss SWE	Group Mean of Max 5-Day Moving Average Daily Loss SWE	Group Mean Period Mean Temp C	Recorded SBB Dust Events
WY 2006	4/12/06	21.4	40	1.7	0.57	1.19	3.6	8
WY 2007	4/18/07	18.8	39	3.3	0.57	1.21	3.8	8
WY 2008	4/19/08	29.3	54	4.0	0.62	1.39	3.7	7
WY 2009	4/19/09	24.2	37	2.9	0.74	1.36	4.4	12
WY 2010	4/19/10	20.1	41	3.1	0.60	1.29	3.5	9
WY 2011	5/3/11	29.4	44	3.8	0.79	1.62	5.4	11
WY 2012	3/21/12	13.8	47	2.3	0.34	0.94	2.9	12
Max	05/03/11	29.40	53.7	4.03	0.79	1.62	5.40	12
Min	03/21/12	13.76	37.2	1.71	0.34	0.94	2.85	7
Range	43	15.64	16.5	2.31	0.44	0.68	2.55	5

Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE

Although some seasons present substantial regional variations in snowpack properties and snowmelt timing and rates across the Colorado mountains, aggregating these fifteen Snotel site data by season further highlights just how different Water Years 2012 and 2011 were (table above). Both years required a similar number of days to fully ablate their snowpacks (entire period following peak SWE), but 2012 peak SWE was less than half of 2011 peak SWE, and melt rates in 2011 were more than double those in 2012. Although air temperature differences would support higher melt rates in 2011, and the role of direct solar energy is reduced by shading at Snotel sites, the shift in 2011 snowmelt season to late May and June also resulted in near maximum solar energy inputs contributing to the Colorado snowmelt energy budget, as the sun approached its seasonal zenith and day length approached the solstice maximum. The much earlier peak SWE and start to snowpack ablation in 2012, in March, resulted in a lower total potential solar energy contribution to the snowmelt energy budget, before SAG.

Given the very dry winter and sub-par snowpacks statewide, below average snowmelt runoff was unsurprising. However, in response to periods of dry, sunny, unseasonably warm weather and sustained exposure of significant dust-on-snow, spring 2012 hydrographs statewide also exhibited early runoff onset at unusually high rates, with a corresponding early and steep descending limb to very low levels.

In addition to the very warm temperatures associated with prolonged periods of dry and sunny weather in late winter and spring 2012, dust-on-snow events D4 (March 6th) through D8 (April 6th) played a significant role in this early statewide runoff, reducing snow albedo and hastening the warming of the snowpack to isothermal (at 0° C throughout) in late March or early April. Those dust layers continued absorbing and adding solar energy to the snowmelt energy budget during subsequent periods of exposure at the snowpack surface in April and May. Most systems produced peak streamflows well in advance of normal timing, at well below-average levels. By early June, snowcover was largely ablated, statewide, and streamflows began a rapid and steep decline to very low levels normally not seen until the end of summer.

THE FOLLOWING SITE-SPECIFIC SUMMARIES ARE INTENDED TO STAND ALONE AS INDIVIDUAL REPORTS:

Berthoud Summit | Grand Mesa | Grizzly Peak | Hoosier Pass | McClure Pass | Park Cone | Rabbit Ears Pass | Senator Beck Basin
Spring Creek Pass | Willow Creek Pass | Wolf Creek Pass

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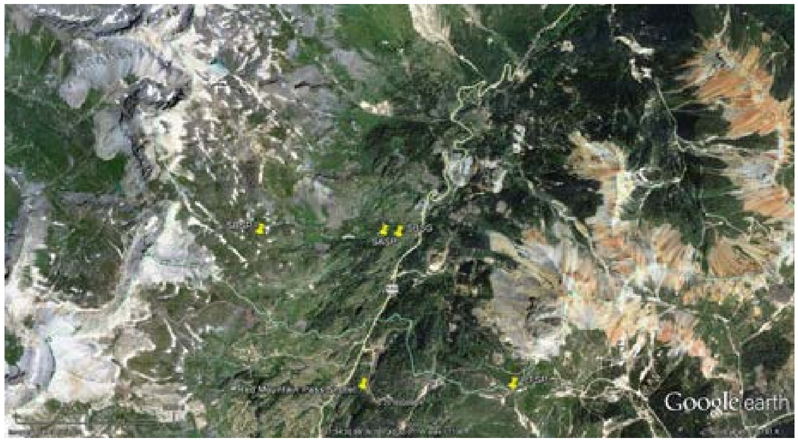

WATER YEAR 2012 CODOS SUMMARY FOR SENATOR BECK BASIN STUDY AREA

Summary | Dust Log | Winter Storm Log | Snowpack | Melt Rate | Stream Flows | Open Questions

SUMMARY

Water Years 2011 and 2012 produced a case study in interannual variability of Colorado snowpack formation and ablation driven in large part by vastly different late winter and spring precipitation, perhaps representing seasonal extremes. On the other hand, the two seasons produced *comparatively* similar dust-on-snow conditions in the Colorado mountains.

Unusually stormy winter weather in spring 2011 resulted in relentless snowfalls interrupting and postponing sustained dust-on-snow effects until late May, just as historically large or record-breaking snowpacks peaked. Dust-in-snow then enhanced the delayed but rapid snowmelt and runoff in June, at a sustained, high rate.

In dramatic contrast, extremely dry late-winter and spring weather conditions in 2012 resulted in very low values of peak SWE and an unusually early and dust-enhanced start to snowpack ablation. Beginning in March, dust-on-snow layers remained exposed at the snowpack surface for prolonged periods, absorbing enough additional solar energy to initiate and enhance snowmelt and runoff well in advance of long-term average timing. That early phase of dust-enhanced snowmelt was then disrupted in April by frequent but small storms. A second phase of more rapid, dust-enhanced snowmelt followed in May and, in conjunction with sub-par snowpacks, generated an early and well-below-normal peak in snowmelt runoff followed by a rapid decline in runoff flows in June to levels normally observed in late summer.

DUST LOG

Dust-on-Snow Events Documented per Month, by Winter
Senator Beck Basin Study Area at Red Mountain Pass – San Juan Mountains

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	**Total**
2002/2003					2		1			**3**
2003/2004							2	1		**3**
2004/2005	0	0	0	0	0	1	2	1	0	**4**
2005/2006	0	0	1	0	1	1	3	2	0	**8**
2006/2007	0	0	1	0	1	1	3	1	1	**8**
2007/2008	0	0	0	0	0	3	3	1	0	**7**
2008/2009	1	0	1	0	1	4	5	0	0	**12**
2009/2010	1	0	0	0	0	1	4	3	0	**9**
2010/2011	0	0	0	0	1	3	3	4	0	**11**
2011/2012	0	2	1	0	0	3	2	4	0	**12**

The Senator Beck Basin Study Area at Red Mountain Pass, operated by the Center for Snow and Avalanche Studies, serves as the baseline sentry site for rigorous dust-on-snow monitoring in Colorado. Dust-on-snow “events” are defined, by CSAS and the Colorado Dust-on-Snow program (CODOS) as a deposition of new mineral material (as distinct from vegetation debris) that is visually discernible, to the naked eye, as a layer at the subalpine Swamp Angel Study Plot or, if dust is falling directly onto an already dirty snowpack surface, an event may be indicated by the visual observation of dust in the sky. Although most events begin during daylight hours, many continue after nightfall, and rare events fall entirely during darkness (these are still generally easily detected in the snowpack). Some very fine aerosol material may be deposited onto the Swamp Angel Study Plot snowpack undetected and also contribute to reduction in snow albedo; except in the case of unknown amounts of black carbon (soot) that may be falling onto our snowpack, these other fine aerosols, such as inversion ‘smog’ or other pollution, are considered negligible contributions in comparison to the albedo impacts of visually discernible dust “events”.

Swamp Angel Study Plot Dust Mass Loading Data - WY 2011
From 0.5m2 samples collected by CSAS, processed by USGS Denver

Dust Event	Date	Visually Estimated Organic Content	Gross Weight 0.5 m2 Sample (grams)	**Estimated Mass Loading Grams/m2**	Notes
D1	19-Feb-11	na	no sample	**na**	Extremely minor event
D2	6-Mar-11	na	no sample	**na**	Extremely minor event
D3	17-20-Mar-11	80%	0.1378	**0.276**	Discrete sample
D4	21-Mar-11	<10%	2.562	**5.124**	Merged sample; D4 value derived from a merged D3-D4 sample, less the D3 sample
D5	8-Apr-11	<10%	0.608	**1.216**	Discrete sample
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D11	29-May-11	na	no sample	**na**	Major dust-on-dust event; discrete sampling infeasible
D2-D11 Merged	**6/14/11 Sample**	**20%**	**7.0646**	**14.129**	**Sample of top few cm after D11-D2 layers had merged; some 'seepage' missed**

Swamp Angel Study Plot Dust Mass Loading Data - WY 2012
From 0.5m2 samples collected by CSAS, processed by USGS Denver

Dust Event	Date	Visually Estimated Organic Content	Gross Weight 0.5 m2 Sample (grams)	**Estimated Mass Loading Grams/m2**	Notes
D1	November 5, 2011	<10%	0.2684	**0.537**	Discrete sample
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D3	December 31, 2011	"mostly"	0.0670	**0.134**	Discrete samples, lots of dark, large, dark (black) organic particles
D4	March 6, 2012	not char	0.1687	**0.337**	Discrete sample of typical brown dust; began dry on slick m/f crust overnight and w/snow next day
D5	March 18, 2012	not char	1.6387	**3.277**	Discrete sample of 'wet' event, 'iced tea' color
D6	March 26, 2012	na	na	**na**	Very minor dust-on-dust event at SBB; discrete sampling infeasible
D7	April 1, 2012	na	na	**na**	Dust-on-dust at SBB; discrete sampling infeasible
D8	April 6, 2012	na	na	**na**	Significant dust-on-dust at SBB; skiff new snow onto D8; discrete sampling infeasible
D9	May 18, 2012	na	na	**na**	Snow all gone at SASP - sampling infeasible, but was very minor dry event
D10	May 23, 2012	na	na	**na**	Snow all gone at SASP - sampling infeasible, but was very minor dry event
D11	May 25, 2012	na	na	**na**	Snow all gone at SASP - sampling infeasible, but was very minor dry event
D12	May 26, 2012	na	na	**na**	Snow all gone at SASP - sampling infeasible, but was major dry event, perhaps largest of season
D4-D8 merged	Sampled May 4	na	3.5336	**7.067**	Merged sample of D8-D4 collected May 4; some infiltration losses already incurred
Estimated D6,7,8				*3.4524*	*Inferred mass, by subtracting measured D4 and D5 events from merged D8-D4 sample*
Measured D1-D8				8.6578	Sum of discretely sampled D1, D2, D3, plus merged D4-D8 sample
Estimated D9-12				2.4 - 3.4	Range of plausible totals for D9-D12, predominately from event D12
Estimated D1-D12				**11 to 12**	**Estimated total mass loading, in grams per square meter**

Throughout the winter season, beginning with the first snowpack until "snow all gone" (SAG) in the spring, CSAS/CODOS collects, as feasible, discrete samples of individual dust layers at Swamp Angel Study Plot. The absence of wind redistribution of new snow containing dust at SASP results in comparatively uniform rates of deposition of dust and snow throughout the SASP site. A 0.5m^2 sample is collected, including snow above and below a new dust layer, and bottled. That sample is then shipped to a United States Geologic Survey in Denver where it is processed by lab technicians with the Geology and Environmental Change Science Center conducting research on "effects of climatic variability and land use on American drylands". Water is evaporated from the dust/snow sample and significant amounts of vegetation debris are noted. The dry dust material is then weighed on high precision scales. The weight of dust from the 0.5m^2 sample is then doubled to estimate the mass loading, of dust, per square meter. Additional concentrated dust samples are collected, without regard to aerial extent, for chemical analysis by USGS. USGS retains and archives both types of samples for future reference.

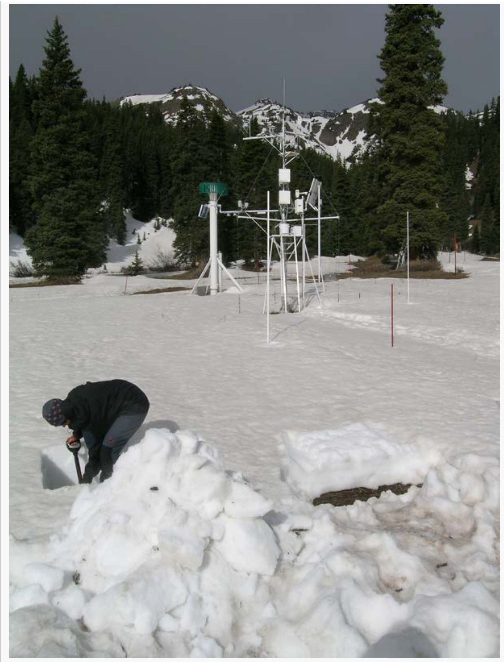
On May 4th, 2012 this 0.5 m2 sample of merged dust layers D4 through D8 was collected at Swamp Angel Study Plot; snow albedo was ~0.48 (48% reflectance). Approximately ¼ of the sample has been removed from the square sampling area and placed in a clean plastic bag. Some infiltration of fine dust entrained in melt water had occurred, so snow was collected down to a depth a few inches below the surface. Such samples are promptly driven to Silverton and immediately transferred to a large Nalgene carboy before melting, and the emptied bag is flushed with distilled water into the carboy to minimize loss of dust material to the bag. After evaporating all liquid, and removing large vegetation particles (pine needles), this sample contained 3.5336 grams of dust per square meter.

As the WY2012 table above indicates in grey, for the first time in our history of observation at Senator Beck Basin, we lost snowcover at our subalpine Swamp Angel Study Plot before the end of the dust storm season. Four additional dust storms, three of which were very minor, fell onto bare ground at Swamp Angel Study Plot in May, precluding dust sampling consistent with our protocol. Nonetheless, all four of those events did fall onto snowpack at the higher elevations of Senator Beck Basin, as dust-on-dust events without any additional snow. Although three of these events were of minimal mass, perhaps comparable to event D3-WY2012, the final, fourth event D12-WY2012 was on a par with the most major dust storms observed in prior seasons, with darkened red skies, major reductions in visibility, and visible dust deposition in Silverton, running into nighttime. In the absence of any SASP sampling of that event, because snowpack had long since melted, CSAS estimates that D12-WY2012 was comparable to event D5-WY2012, and perhaps larger. Therefore, our estimate is that those portions of Senator Beck Basin remained that snow covered until May 26, 2012 experienced a total mass loading of 11-12 grams per square meter, +/- 1 gram.

The total number of dust-on-snow events in WYs 2011 and 2012 (at 11 and 12 dust storms, respectively) and their season dust mass loading totals were notably similar, at 14 grams per square meter in WY2011 and an estimated 11-12 grams per square meter in WY 2012 (see below). Despite those similarities, diametrically different late winter and spring weather during the past two seasons resulted in dust having very different effects on snowmelt processes at Senator Beck Basin and throughout the State.

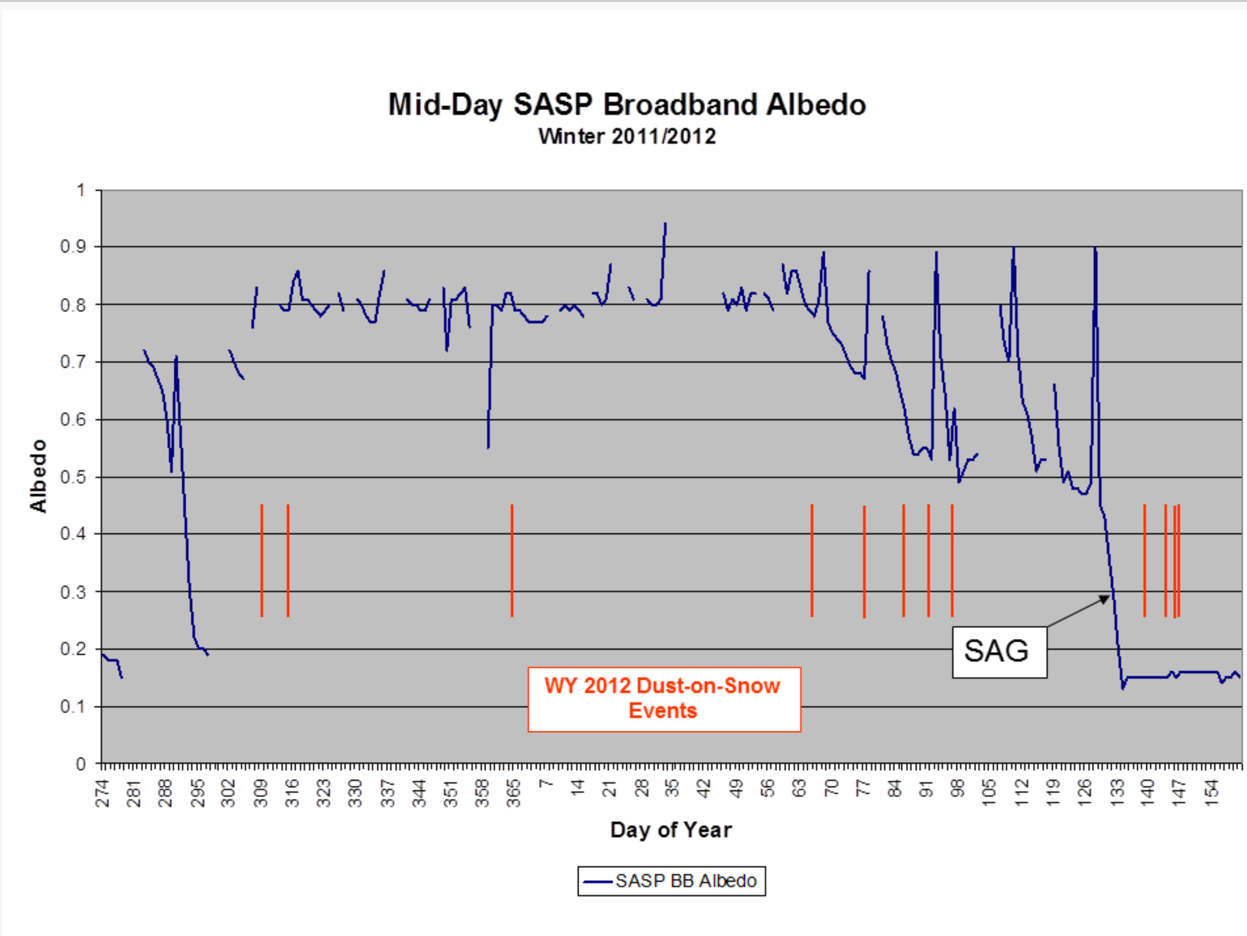
Eleven dust events occurred in the late winter and spring of 2011. However, relentless accumulation of late winter and spring snow routinely buried new dust layers at Senator Beck Basin and restored high snow albedo values, until the end of May. Then, on May 29th, the final and perhaps largest dust event of the season, D11-WY2011, fell onto the surface of what was still close to peak SWE accumulation at the Swamp Angel Study Plot. The first three weeks of June 2011 were entirely dry and sunny enabling D11 to quickly ablate underlying snow and merge, in rapid succession, with underlying dust layers.

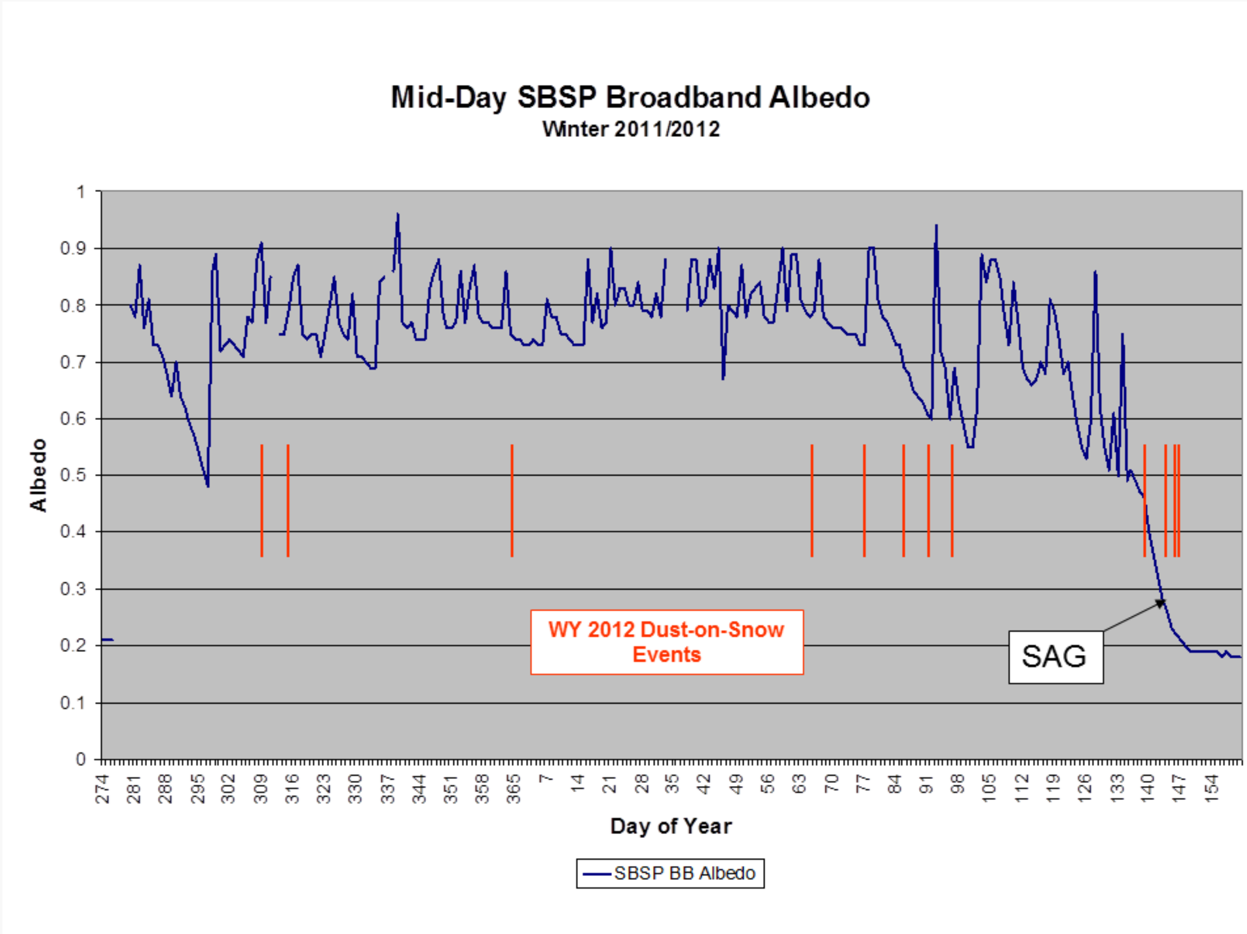
In juxtaposition to 2011, late winter and spring 2012 were exceptionally dry, with widely spaced and comparatively small winter storms at Senator Beck Basin. Only 156 mm (6.1”) of precipitation fell in Mar/Apr/May 2012, versus 516 mm (20.3”) in Mar/Apr/May 2011. As a consequence of that dry weather, dust-on-snow event D4-WY2012, on March 6th, and subsequent dust events that merged with and enhanced dust layer D4 were only occasionally



Swamp Angel Study Plot on May 7, 2012, with Profile #17 under excavation as the snowpack rapidly approaches "snow all gone" (SAG). Snow albedo ranged from near 0.50 (50% reflectance) in early May to ~0.45 near SAG.

and usually briefly buried under clean new snow for the remainder of the sharply curtailed spring 2012 snowmelt season. Initial reductions in snow albedo from event D4 in early March at Senator Beck Basin were initially small. However, event D5, on March 18th, 2012 added substantial additional dust to the snowpack and soon emerged at the surface. Incremental additions of dust events D6-8, often as dry events without precipitation, further reduced albedo values. Following event D8, which fell on April 6th directly onto the merged D7-4 dust layers at the snowpack surface, albedo values at Swamp Angel Study Plot were 0.49 to 0.55 (indicating 49-55% reflectance of incoming solar energy). Albedo values in clean snow in early April 2011 were 0.60 to 0.68. During the exceptionally dusty spring of 2009, albedo at SASP fell as low as 0.35-0.40 at the end of the season.





Plots of average "broadband" snow albedo from 1200-1300 hours each day of WY 2012 snowpack at the Swamp Angel and Senator Beck Study Plots in Senator Beck Basin Study Area. Gaps in the data represent days during which snow covered the up-looking sensor measuring incoming, short-wave radiation (the "broad band" pyranometers). Data at either end of the plot represent albedo of bare soil or vegetation on the ground. Red bars show WY 2012 dust-on-snow events, by date. The point of "snow all gone" (SAG) is indicated, and albedo values for the preceding day or two were reduced by dark soil seen through the shallow, wet snow by the down-looking pyranometer. Albedo is calculated as the ratio of reflected radiation to incident (incoming) radiation upon a surface; valid snow albedo values in these plots range from ~0.3 (30% reflectance) to ~0.9 (90% reflectance). Both sites experienced declines in snow albedo beginning with event D4 (March 6th), frequently reversed by clean snow.

WINTER STORM LOG

The Center for Snow and Avalanche Studies has maintained a log of "winter storms" since the winter of 2003/2004. Winter Storms are defined as a snow precipitation event containing at least 12 mm (~ 0.5") of water equivalent, as measured in 1 mm increments at the Swamp Angel Study Plot using an ETI precipitation gauge, and with no break in precipitation greater than 12 hours. A number of storm parameters are logged, including allocations of storm precipitation to rain or snow in early and late winter. Weather events which meet the Storm criteria are sequentially numbered throughout the season, but all precipitation is, of course, recorded and tallied. The complete CSAS Storms and Precip Data record presenting detailed and summary Storm datasets and graphs is contained in an Excel workbook linked on our website.

October through May Totals	Season	Winter Storms	All Days Precip	All Precip - mm	Snow precip - mm	Rain precip - mm
	2003/2004	23	92	749	711	38
	2004/2005	20	107	890	842	48
	2005/2006	26	113	833	801	32
	2006/2007	27	105	910	880	30
	2007/2008	29	119	1024	974	50
	2008/2009	24	108	916	797	119
	2009/2010	24	115	836	832	4
	2010/2011	33	124	1151	1110	41
	2011/2012	23	86	660	656	4
Period of Record Working Means		25	108	885	845	41

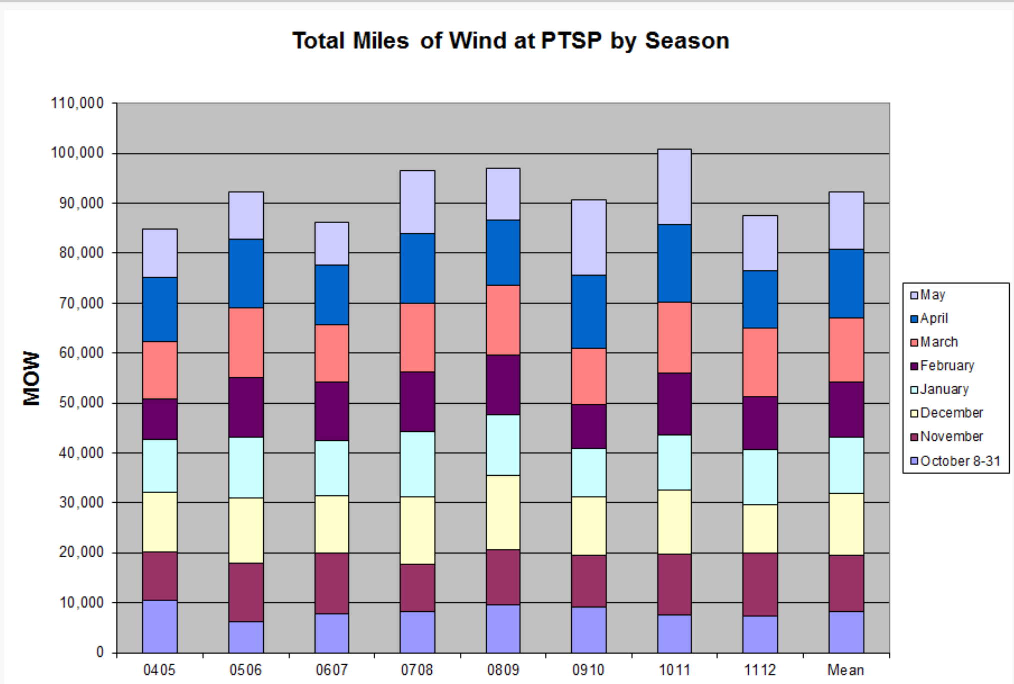
The table above presents summary statistics for the nine winter seasons in our period of record. Since and including the winter of 2003/2004, our Senator Beck Basin Study Area has experienced between 20 and 33 numbered winter Storms from October through May, with a working mean of 25 Storms per season. We have also observed 3 Storms in June.

Winter 2011/2012 produced 23 numbered winter Storms, two fewer than the working mean and three more than the minimum of 20 Storms in 2004/2005, but with the least total precipitation (including non-storm precipitation), at 660 mm (26.0”), of any October through May period in our short history. Winter 2010/2011, on the other hand, produced the most numbered winter Storms and the highest precipitation total for the Oct-May period.

A closer look reveals that the eighteenth storm of the season fell at the very end of February during both winters 2010/2011 and 2011/2012. October through February season precipitation totals were 635 mm (25.0”) in 2011, including 41 mm (1.61”) of rain, compared to 504 mm (19.8”) in 2012, with only 1 mm (0.04”) of rain. Spring snow storms can be the product of mesoscale processes such as local convection. But, if most early- and mid-winter Storms, as we define them, require weather events driven by non-local, synoptic scale atmospheric dynamics creating weather opportunities, then the large variations in Storm precipitation yields, from the identical number of Storms between October 1 and March 1 in 2010/2011 and 2011/2012, is of interest.

Our own hand drawn strip charts of those winter seasons, with bar graphing of daily precipitation totals (in blue), reveals that Storms #18-19 in 2010/2011 produced generally larger amounts of precipitation than their numbered counterparts in 2011/2012. Storm #8 in particular, a six-day event from December 18-23, 2010 delivered 105 mm (4.1”) of water equivalent increasing snowpack depth by 82 cm (32”), an outsized contribution to the WY 2011 snowpack. Recent investigations of these very large winter storms led by Dr. Marty Ralph at NOAA, in Boulder, is exploring the connection between “atmospheric river” events coming onshore from the Pacific Ocean and snowpack formation in Colorado. These atmospheric rivers (or ARs), are extremely concentrated plumes of low level water vapor emanating from the Pacific and delivering extreme precipitation events to coastal areas, eventually traveling as far inland as Colorado. CSAS has contributed Senator Beck Basin Storm data to Dr. Ralph’s effort to document and understand these AR events and looks forward to assisting in that ongoing research.

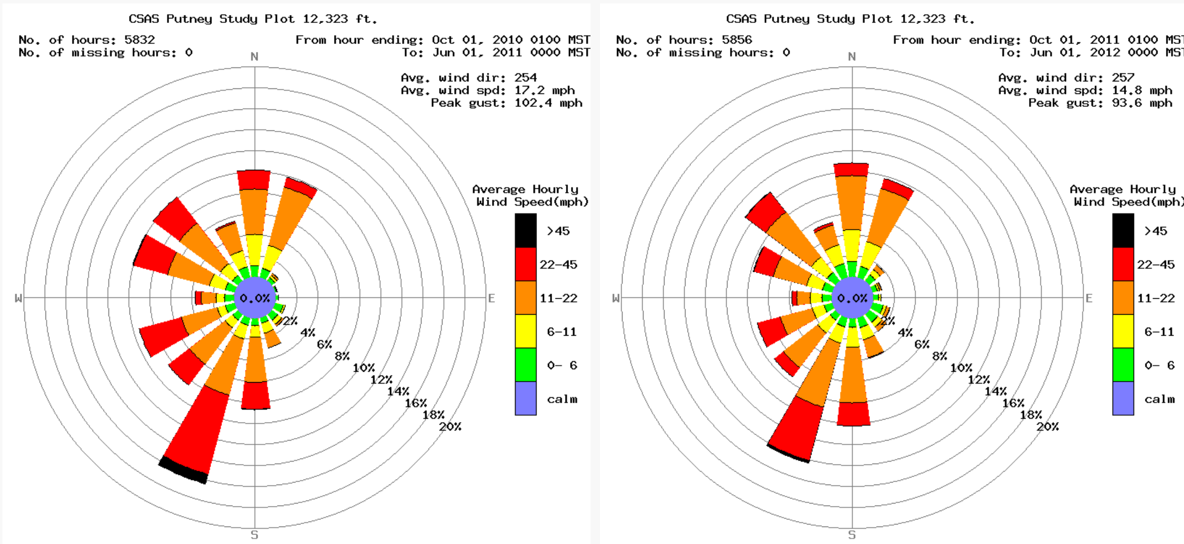
Further, it is also increasingly apparent that synoptic scale weather dynamics, rather than local winds, are required to generate wind fields potent enough to mobilize desert dust in the Colorado Plateau’s many source areas and then deliver that dust throughout the Colorado mountains in the concentrations we’re observing. Soil conditions in the source area must be favorable for dust mobilization as/when these winter and spring storms pass over the Colorado Plateau. Since those soil conditions are not always favorable, only some of our numbered winter Storms also deliver dust-on-snow, as “wet” depositions associated with new snow. However, as we experienced several times in spring 2012, ‘dry’ wind events driven by synoptic scale atmospheric dynamics, but without associated precipitation, can also bring dust storms to the Colorado mountains.



Total “miles of wind” passing through the Putney Study Plot, by month and winter season. One hour of wind averaging 30 mph at PTSP would yield 30 miles of wind.

CSAS monitors “miles of wind” at our Putney Study Plot near Red Mountain Pass. Compared to the winter of 2010/2011, which produced the most miles of wind in our period of record, last winter 2011/2012 was substantially less windy, particularly in March, April and May, when precipitation also fell of. Although dust event D5-WY2012 was a “wet” deposition, in association with Storm #20 in mid-March, all the subsequent dust events in March, early April, and late May, were dry dust storms without associated precipitation. The synoptic chracteristics of those spring 2012 dust storms were adequate to generate strong wind fields but did not include moisture supplies capable of producing significant snowfalls (as compared to the numerous “wet” dust events of Mar/Apr/May 2011 that were associated with major winter storms).

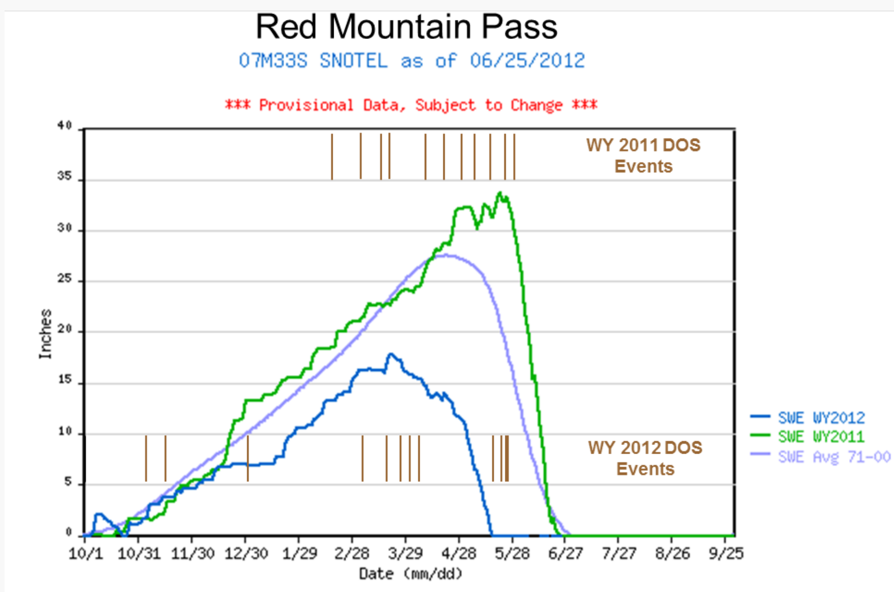
CSAS has posted "wind rose" plots of wind speed and direction for each dust-on-snow event of WY 2012, and all prior years. The two wind roses shown below are for the periods October 1 through summer solstice of WY 2011 and WY2012 (seasonal wind roses for our entire period of record are also available). Although very similar in overall pattern, these two seasons represent the maximum (2010/2011) and the minimum (along with 2005/2006) season average speeds. Winter 2011/2012 shows slightly more due south wind, and slightly less SW,WSW, and WNW wind than 2010/2011, and fewer hours of wind averaging more than 22 mph (shown as red and black blocks).



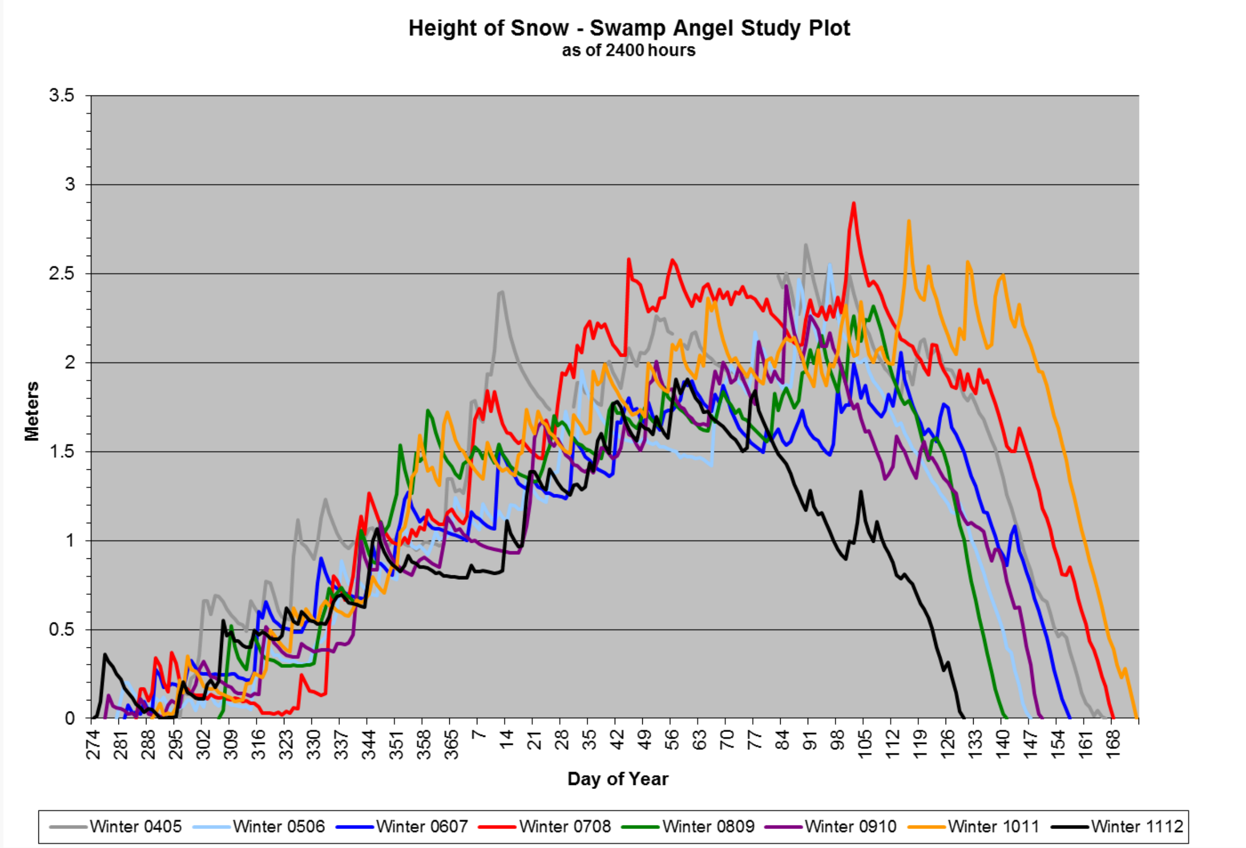
Putney Study Plot hourly wind speed and direction data from October 1 through May 30 of winters 2010/2011 and 2011/2012. Direction data are grouped in 22.5° sectors and speed subdivided into six classifications, including "calm". Concentric rings show the percentage of contribution, for the entire season, of a particular vector (i.e., due south) and/or speed group within a sector.

SNOWPACK

Water Year 2012 snowpack formation at the Red Mountain Pass Snotel began at near-average rates in early winter before slipping into the lower quartile of cumulative SWE values by December and remaining there until peak SWE. Due to the very dry late-winter and spring experienced throughout Colorado, WY 2012 peak SWE, at only 17.8", fell far short of the 1971-2000 average of 27.6" and fell within the lower quartile of values for the entire period of record at that site. The year before, WY 2011 peak SWE, at 33.7", was roughly double that of this WY 2012, and within the period of record's upper quartile. Peak SWE 2012 also occurred very early in the season, on March 22nd, nearly one month earlier than the 1971-2000 average date of peak SWE of April 21st and two months earlier than the WY 2011 May 22nd date of peak SWE. *Further, WY 2012 "snow all gone" (SAG) at Red Mountain Pass Snotel occurred four days earlier than the date of peak SWE in WY2011*. Differences in peak SWE timing and amounts were less dramatic at the Lizard Head Pass Snotel between WY 2011 and 2012, but both seasons produced below average values of peak SWE.



Red Mountain Pass Snotel SWE accumulation and ablation for Water Years 2011 and 2012, with dust-on-snow events shown, by date, as brown bars for both water years (as observed at the Senator Beck Basin Study Area's Swamp Angel Study Plot, 2 km to the north).



Height of snow (snowpack depth) data for Winters 2004/2005 through 2011/2012, in meters.

Snowpack data from the Center for Snow and Avalanche Studies' Swamp Angel Study Plot (SASP) at 11,060' in the Senator Beck Basin Study Area, 1 km north of the Red Mountain Pass Snotel, tell a similar story of year-to-year differences. The extremely well sheltered and relatively isolated, subalpine open meadow location of SASP provides an ideal site for monitoring undisturbed snowpack properties without the spatial variability introduced by wind redistribution of snow, tree shading, and human disturbance. SASP often benefits from light orographic precipitation occurring on the north side of Red Mountain Pass that does not reach the Red Mountain Pass Snotel site located just 1 km south of the Pass and at roughly the same elevation as SASP.

Hourly measurements of SASP snowpack depth show that WY 2012 snowpack depth peaked at 1.97 m (78") on February 28th, 2012, our lowest season maximum to-date and 0.83 m (33") less than and nearly two months earlier than the WY 2011 peak depth of 2.80 m (110") on April 26th, 2011, our second deepest maximum depth. Snowpack total SWE is measured manually at SASP in weekly formal snowpack profiles. In Profile #20, on May 23rd, 2011 the snowpack contained 999 mm (39.3") of SWE. Another 18 mm of additional snow precipitation fell at SASP the next day, increasing the actual WY 2011 peak SWE value for the season to near 40". In contrast, profile #7, on March 26th, 2012 documented our highest measured SWE value for WY 2012 at just 542 mm (21.3"), not long after the only significant winter storm of March. Snowmelt at SASP outpaced additional snow accumulations after that date. Given the short period of record at SASP, no mean statistic for expected snowpack depth has been estimated to-date. Finally, these back-to-back winters also produced the earliest (WY2012) and latest (WY 2011) dates of "snow all gone" (SAG) at SASP, on May 11th and June 23rd, respectively.

Snowpack temperatures are also monitored at SASP, with an array of five automated thermistors monitoring the snow/ground interface and the snowpack above the ground at 10 cm intervals, with an infrared thermometer monitoring the snowpack surface "skin" temperature, and with a specialized digital thermometer during our routine snowpack profiles, at 10 cm intervals over the entire depth of snow. Based on those data, the SASP snowpack appears to have become isothermal at 0° C throughout on/about April 1st, 2012, at a depth of 121 cm (48"), a mean density of nearly 350 kg/m3 (35% water by volume) and with WY 2012 dust layers D6, D5, and D4 merged at the snowpack surface. The year before, the SASP snowpack was effectively isothermal on/about April 18, 2011 at a total depth of 202 cm (80"), with a mean density estimated at ~400 kg/m3 (40% water by volume) and with just one dust layer near the surface, D5-WY2011 (Profile #15). Extremely thick and tough ice layers in Profile #15 unfortunately prevented accurate SWE measurements, without damaging our equipment.

Given the substantially larger amount of total ice (snow) mass to warm to 0° C at SASP in spring 2011, compared to spring 2012, prolonged exposure of dust layers D4-8 at the snowpack surface in March and early April was likely the determining factor in producing an isothermal snowpack by April 10, 2012, two weeks earlier than in 2011, even despite considerably more clear nights in March and early April 2012, and commensurate radiant cooling of the snow surface, than in March and early April 2011, with scant clear nights.

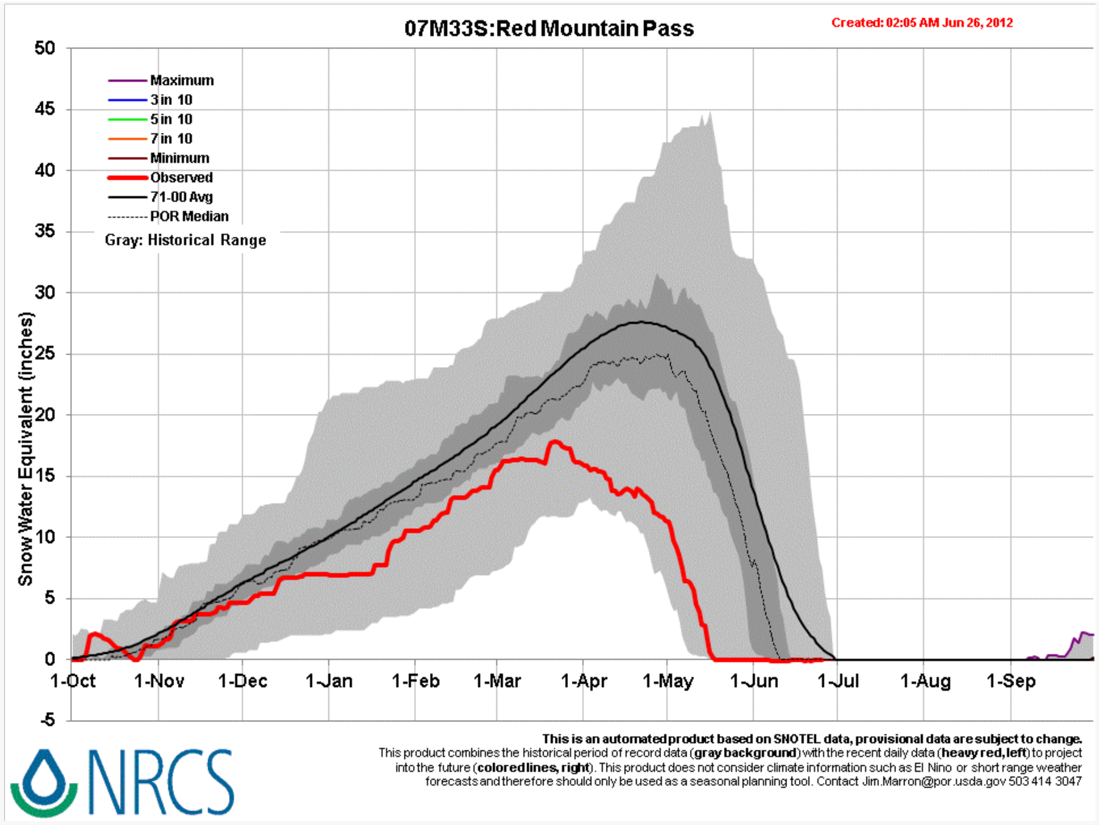
Red Mountain Pass Snotel Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Period Add Precip	Period Mean Temp C	Adjusted Daily Mean Loss SWE	Maximum 5-Day Moving Average of Daily Loss of SWE
WY 2006	4/8/2006	24.4	50	1.2	3.1	0.51	1.36
WY 2007	5/9/2007	23.7	34	1.7	4.7	0.75	1.28
WY 2008	4/14/2008	34.4	66	4.3	2.9	0.59	1.56
WY 2009	4/19/2009	27.5	37	1.8	4.3	0.79	1.34
WY 2010	4/8/2010	24.2	54	3.7	1.5	0.52	1.62
WY 2011	5/22/2011	33.7	33	1.4	6.8	1.06	1.74
WY 2012	3/22/2012	17.8	57	2.2	2.2	0.35	0.86
Max	05/22/11	34.4	66	4.3	6.8	1.1	1.7
Min	03/22/12	17.8	33	1.2	1.5	0.4	0.9
Range		16.6	33	3.1	5.3	0.7	0.9
Median		24.4	50	1.8	3.1	0.6	1.4

Analysis of Red Mountain Pass Snotel data for 2006-2012 snowmelt seasons showing date and quantity of peak SWE, days from peak SWE to "snow all gone" (SAG), total additional precipitation after date of peak SWE, an "adjusted" mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG. Taken as a whole, the spring 2012 snowmelt season produced the lowest mean daily melt rates measured at the Red Mountain Pass Snotel since 2006, at just 0.35" SWE loss per day.

This discussion references CODOS Snotel site data and analyzes rates of snowmelt from Spring 2006 to the present, spanning the period during which we've rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. As discussed in prior CODOS Updates, Snotel sites typically exhibit a radiative regime where surrounding trees reduce the access of incoming solar radiation to snowpack over the SWE measuring snow pillow, and where re-radiation of long wave energy from that vegetation and a reduced skyview may sustain periods of surface snowmelt during nighttime hours. The Red Mountain Pass Snotel site does exhibit some of these complicating characteristics and, like many Snotel sites (Berthoud Summit Snotel is an exception), is not an ideal site for monitoring the maximum effects of dust-on-snow on snowmelt timing and rates, compared to the open meadow at Swamp Angel Study Plot where comparatively unimpeded solar access optimizes dust-enhanced snowmelt energy budgets. Comparison of snowmelt behaviors between the Red Mountain Pass Snotel site and the Swamp Angel Study Plot may inform the interpretation of Snotel snowmelt data when dust-on-snow is present at those Snotel sites.

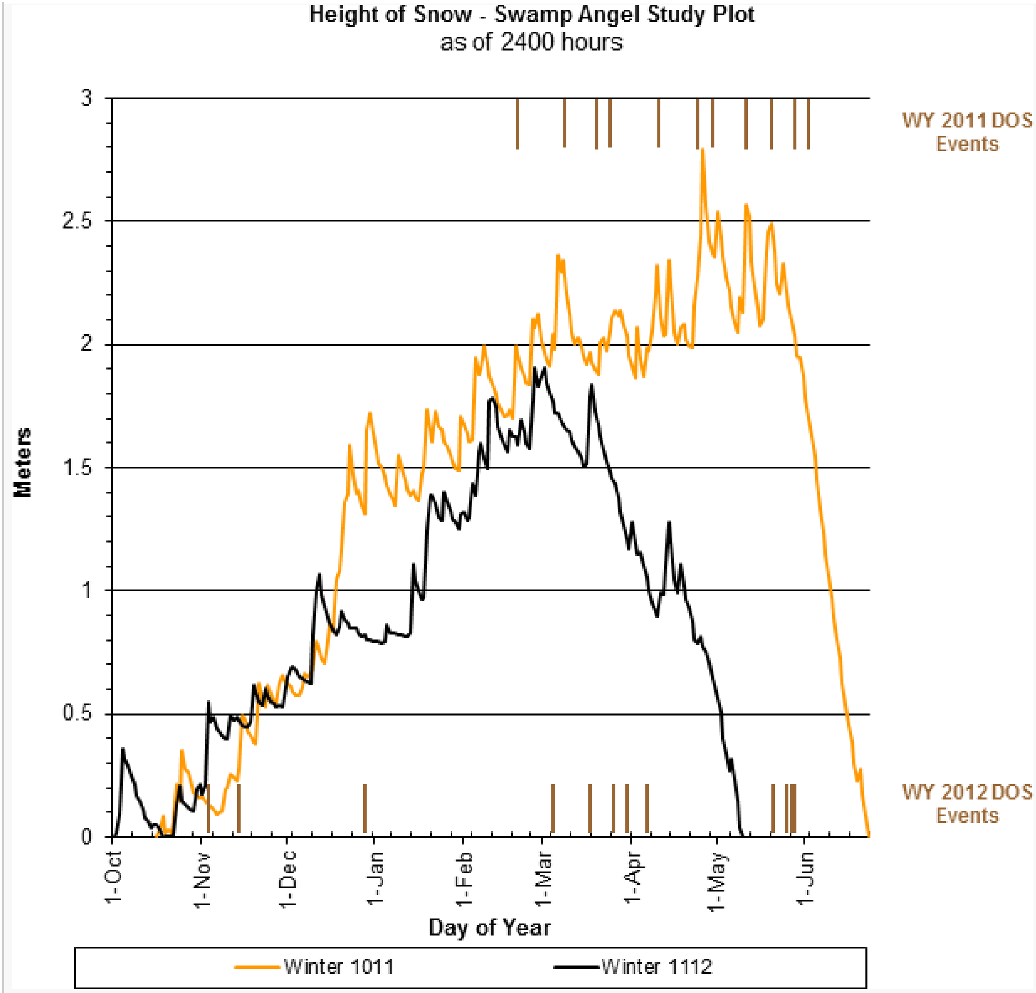
During WY 2012, three fall and early winter dust storms were observed low in the snowpack at Senator Beck Basin. Event D3 was extremely faint at Senator Beck Basin and often not seen at all at other CODOS locations. While early season dust can result in loss of early season snowpack on south aspects, those three early events played only a small role in spring snowmelt, where November snow was still present at all. At the other end of the season, four dust-on-snow events fell after the date of SAG at our Swamp Angel Study Plot and many Snotel sites in WY2012. Those later dust events did nonetheless further reduce snow albedo on the remaining snowpack at higher elevations and on shady aspects in Senator Beck Basin and in the headwaters of the Uncompahgre, Animas, and Rio Grande watersheds nearby.



WY 2012 SWE accumulation and ablation at Red Mountain Pass Snotel, with upper and lower quartiles of period of record shown in light grey, middle quartiles in dark grey surrounding median trace for period of record, and mean trace for 1971-2000 period.

As the Snotel chart showing both WY 2011 and WY2012 clearly shows, snowmelt in late spring 2011 occurred in a single, steep plunge from peak SWE to SAG averaging just over 1" of SWE loss per day. In contrast, spring 2012 snowpack ablation actually occurred in two phases, at distinctly different rates. After two weeks without precipitation in early March, Storm #20 resulted in the season's Peak SWE of 17.8" at the Red Mountain Pass Snotel, on March 21st and 22nd. Storm #20 also deposited dust event D5, which eventually emerged during the subsequent dry period and was augmented by D6 (March 26), D7 (April 1) and D8 (April 6). Low rates of snowpack ablation following Storm #8 resulted in some 3" of SWE loss by the 10th of April, an average rate of just 0.15" per day. Because of the moderate shading from adjoining trees at this site, and light snow on April 2nd, dust emergence was likely slower here than in open terrain (like Swamp Angel Study Plot) and snowpack warming to 0° C may have also been delayed into early April.

A period of unsettled and cooler weather in mid- and late-April, with winter Storms #21, 22 and 23, stalled the snowmelt cycle, adding some 2" of SWE and restoring higher snow albedo values to the snowpack. In early May dry weather resumed and SWE losses accelerated. Dust re-emerged under increasing solar inputs and unseasonably warm temperatures, prolonging overnight surface melt at this site since radiant cooling was inhibited by surrounding trees. The remaining 11.3" of SWE on May 1st were gone by May 18th, 2012 (coincidentally the date of dust event D9) for an average melt rate of 0.63" SWE per day during this second phase of snowmelt. May 18th was very nearly the earliest date in the entire period of record at the Red Mountain Pass Snotel for "snow all gone" (SAG), and was actually earlier than the date of peak SWE in the preceding spring of 2011 (SAG was on June 24, 2011).



As at the Red Mountain Pass Snotel, spring 2011 snowmelt at SASP began very late and occurred as a single, sustained, high-rate plunge from near-peak SWE to SAG. And, as at the Snotel, in 2012 SASP experienced a multi-phased snowmelt season consisting of three, rather than two, distinct episodes of increasingly rapid snowpack ablation.

No melt-freeze snow was observed in our March 5th profile #6, which contained considerable cold content. Snow profile #7 at Swamp Angel Study Plot, on March 26th, produced our highest measured SWE value for WY 2012 at 542 mm (21.3"), not long after Storm #20. In that profile we observed dust layer D5 in the Storm #20 new snow and substantial evidence of melt/freeze cycles in that and another near-surface layer. Later that day, dust event D6 fell onto the snowpack surface. On March 26th the snowpack was on the verge of becoming fully isothermal at 0° C throughout, and became isothermal in early April. Since melt energy contained in free water percolating down into the Swamp Angel Study Plot snowpack was still being consumed by the cold content of the underlying snowpack, and warming that snow to 0° C, little or no snowmelt discharge was exiting the SASP snowpack in March. Despite that, some losses of SWE very likely occurred at the snowpack surface through sublimation and evaporation during prolonged periods of dust exposure in March (see the Open Questions below). Meanwhile, the Senator Beck Basin stream gauge registered an uptick in flows beginning on March 24th, fed by actively melting south-facing slopes in the lower elevations of Senator Beck Basin near SASP, where the snowpack had long-since become isothermal and dust was extensively exposed.

As the SASP snowpack approached isothermal, and dust layers D6 and D5 merged at the snowpack surface, SWE losses dramatically accelerated in a second phase of snowmelt. Profile #9, on April 2nd, showed a loss of 117 mm (4.6") of SWE in the seven days since Profile #7, a loss averaging 0.66" per day.

Stormy weather resumed on April 11th and contributed 74 mm (2.9") of precipitation (SWE) to the snowpack in a series of three dust-free storms that temporarily buried merged layers D6/D5 and restored higher snow albedo to SASP. Nonetheless, the snowpack remained isothermal, some melt continued to leave the snowpack, and the merged dust layers re-emerged at the surface. On April 30th, just 283 mm (11.1") of SWE remained in the snowpack, down from the 425 mm (16.7") measured on April 2 in Profile #9. That difference of 142 mm (5.6"), plus the 74 mm of additional SWE that fell during April, results in a net loss of 216 mm (8.5") of SWE during April, at an average of 0.29" per day, even with 15 days of recorded precipitation (and corresponding reductions in solar inputs).

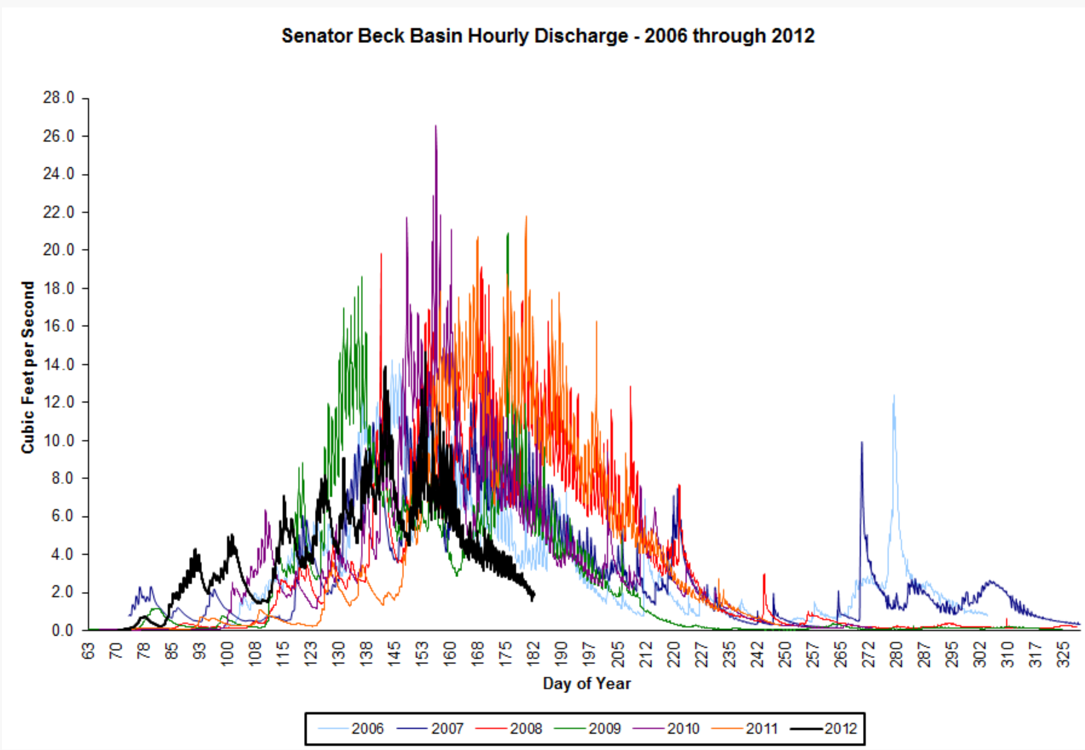
The final phase of SASP snowpack ablation began at the end of April. By May 11th, SASP recorded "snow all gone" (SAG), losing all of the 283 mm of SWE measured April 30th plus an additional 8 mm of new precipitation, for a net loss of 291 mm (11.5") of SWE in 11 days, an average rate of 1.04" loss per day.

When evaluated as a single snowmelt cycle, comparable to the [Red Mountain Pass Snotel analyses in the table above](), SASP required some 56 days to ablate, to SAG, 542 mm (21.3") of SWE measured March 26th plus 94 mm (3.7") of subsequent additional snow precipitation, for a total of 638 mm (25.1"), at an average of 11.4 mm (0.45") of SWE loss per day, or 129% of the 0.35" rate of daily SWE loss at the nearby Red Mountain Pass Snotel site. Although this analysis examines just one snowmelt cycle, and the proportion of increase in melt rate at SASP is likely to vary from year to year, these data may suggest the magnitude of difference in melt rates, given roughly equivalent snowpack and dust loading, between shaded and open sites.

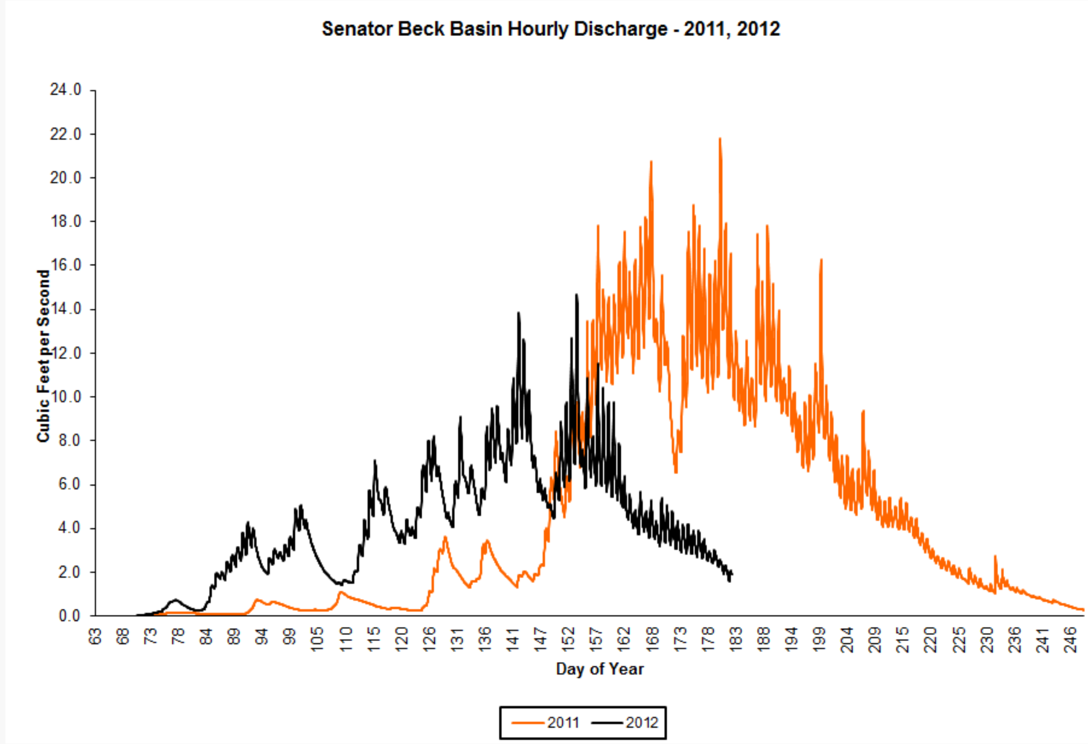
STREAM FLOWS

Senator Beck Basin is a 219 acre headwater catchment of the Uncompahgre River. The southern boundary of Senator Beck Basin adjoins Mineral Basin, a headwater catchment of the Animas River, and the western boundary adjoins Ingram Basin, a headwater catchment of the San Miguel River. Senator Beck Basin is just 13 miles northwest of the Rio Grande headwaters near Stony Pass.

Under its US Forest Service Special Use Permit for Senator Beck Basin, CSAS installed the Senator Beck Stream Gauge (SBSG), a broad-crested, notched, concrete weir structure, at the pourpoint of Senator Beck Basin in fall 2004. Automated stage, water temperature, and electrical conductivity sensors capture hourly and 24-hour summary data. Manual discharge measurements by State of Colorado technicians were utilized by the original contractor to develop the SBSG discharge function over the subsequent two seasons and data begin in WY 2005. In June 2012, a manual measurement of discharge performed immediately upstream of the weir by a USGS technician, at SBSG stage of 0.68' feet, found a 7% variance between the calculated SBSG discharge (4.99 cfs) and the manual measurement of discharge (4.66 cfs).



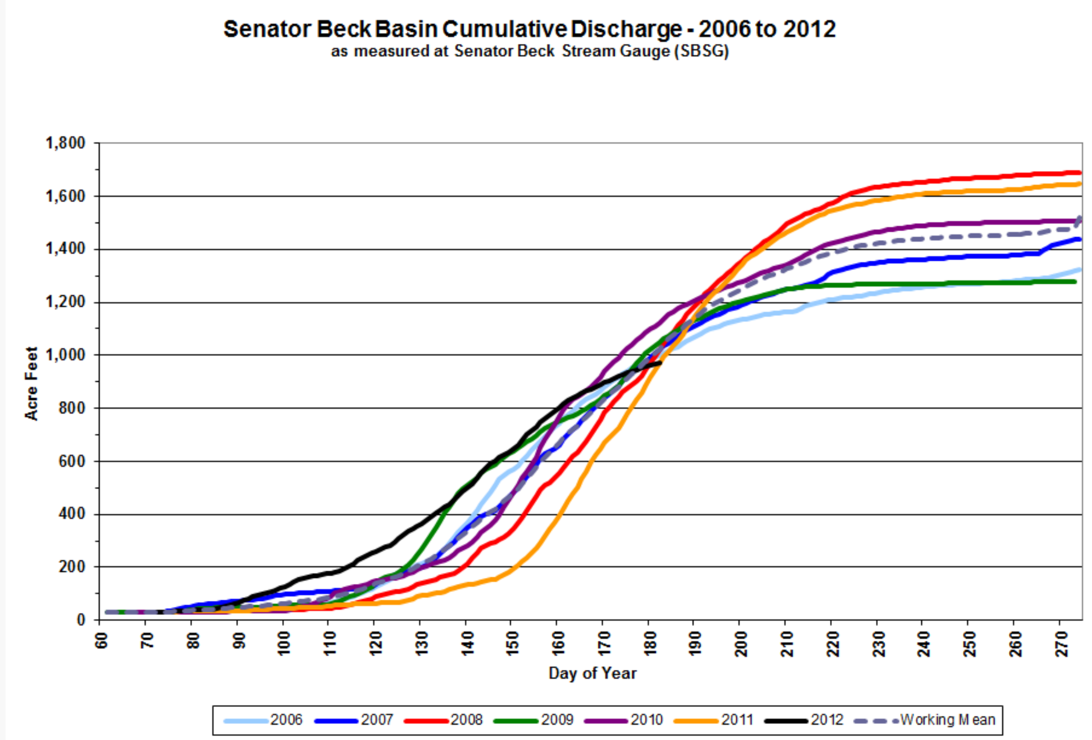
Hourly discharge, by day of year, at the Senator Beck Stream Gauge for spring, summer and fall of 2005 through 2012 (to-date). Automated sensors begin measurements in March, to prevent freezing damage during winter months. The plot below extracts WYs 2011 and 2012 from the plot above, for clarity.



Senator Beck Basin Discharge Chart 2011-2012

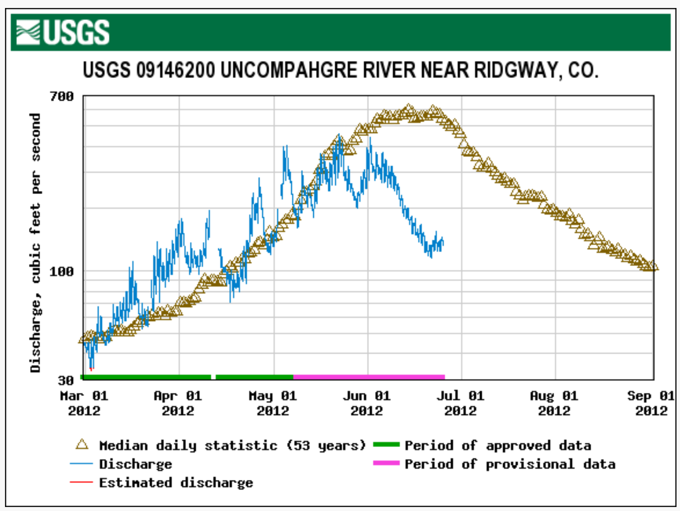
Spring 2012 snowmelt runoff at SBSG produced a series of small surges above base flow in March, as the snowpack on south-facing slopes in lower Senator Beck Basin became isothermal and dust-enhanced snowmelt quickly consumed the shallow snowpack. Runoff gradually accelerated in April, as more aspects and elevations became isothermal and merged dust layers D5/D4 periodically emerged between fresh snowfalls. Basin snowpack rapidly decreased in early May, with SAG at our alpine Senator Beck Study Plot (12.180') on May 22nd. Dry, sunny weather in late May produced a two-part final surge in runoff, interrupted by an interlude of colder weather driven by a dry and very windy intrusion of cold air and the final dust event of the season, D12, on May 26th.

Just as we observed in Senator Beck Basin snowpack formation and ablation, the past two spring runoff seasons also produced extremes of Basin streamflow behavior. Although spring 2009 produced our highest observed instantaneous flows, spring 2011 stands apart as our most delayed runoff cycle, with snowpack persisting in Senator Beck Basin into July as monsoon rains arrived and, along with dust-on-snow, completed the snowmelt cycle. Spring 2012 snowmelt runoff at SBSG began fully forty days earlier than in 2011 and was rapidly waning by early June, just as 2011 was beginning to peak. Spring 2012 will show the lowest net yield from snowmelt in our period of record at SBSG.



Cumulative discharge at the Senator Beck Stream Gauge (SBSG) for spring, summer and fall 2006-2012, with a "working mean" shown. Water Year 2012 snowmelt discharge has lagged well behind all prior seasons.

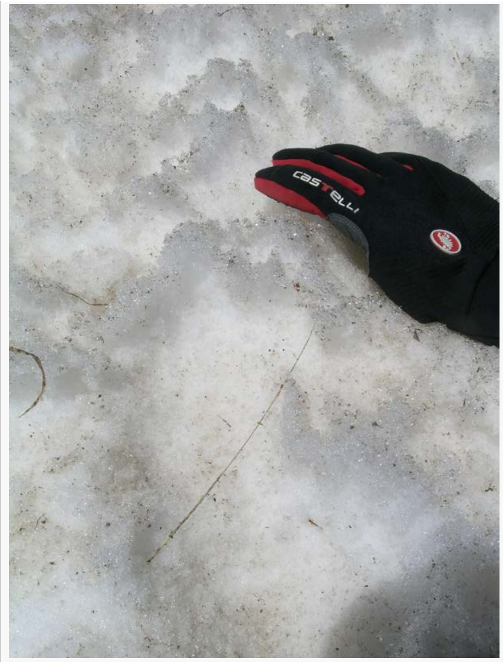
Farther downstream, data at the USGS Uncompahgre River near Ridgway gauge mirror the early and reduced snowmelt runoff observed at SBSG, although snowmelt at the lower extremes of snowpack in the watershed produced even earlier elevated flows there. March and early April saw well above average discharge levels for that period until dropping back to median levels during the stormy weather of mid-April. Subsequent episodes of dust-enhanced surging and retreat followed. By mid-May, snowpack had been substantially ablated in the watershed. Peak runoff on May 23rd arrived several weeks in advance of the median normal peak flow date. A steep decline in June rapidly dropped to flow levels normally seen in mid-August. Overall, this hydrograph presents an advance in the timing of WY 2012 runoff, with the center of the substantially reduced runoff mass occurring several weeks earlier than normal. Hydrographs for the Animas, Dolores, and San Miguel rivers show very similar, if not more pronounced, changes in timing and total runoff volume.



WY 2012 USGS Uncompahgre River near Ridgway Stream Gauge data for a 149 sq. mi. drainage area in the Uncompahgre River watershed, above 6,878'. Current year and historic data reflect withdrawals for irrigation upstream.

OPEN DUST-ON-SNOW AND SNOW HYDROLOGY QUESTIONS

Sublimation of snow/ice, from the solid phase directly to the vapor phase, has long been recognized as a source of SWE losses in mountain snowpacks. In the course of our several seasons of dust-on-snow fieldwork at Senator Beck Basin, and elsewhere in Colorado, CSAS has observed that dust-on-snow can result in increased and patterned surface roughness in the snowpack surface, as dust emerges and enhances melt. The photo to the right illustrates incipient sun cup formation, and prior Updates have shown more advanced stages of this form of dust-enhanced roughness. Dust entrained in new snow is especially prone to developing complex structures including incipient snow penitentes in tightly spaced, regular rows oriented toward the solar zenith.

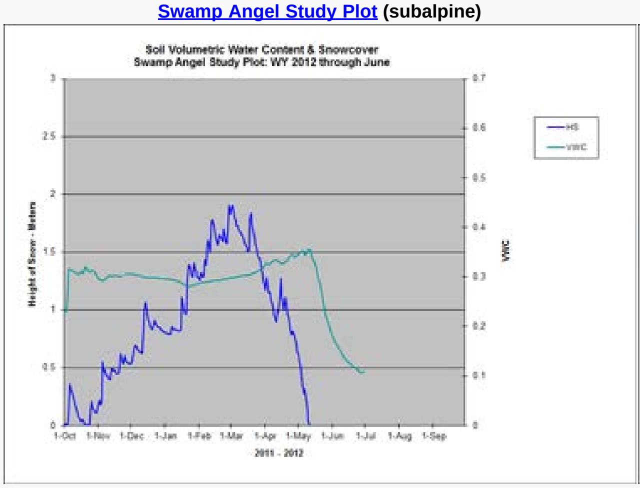
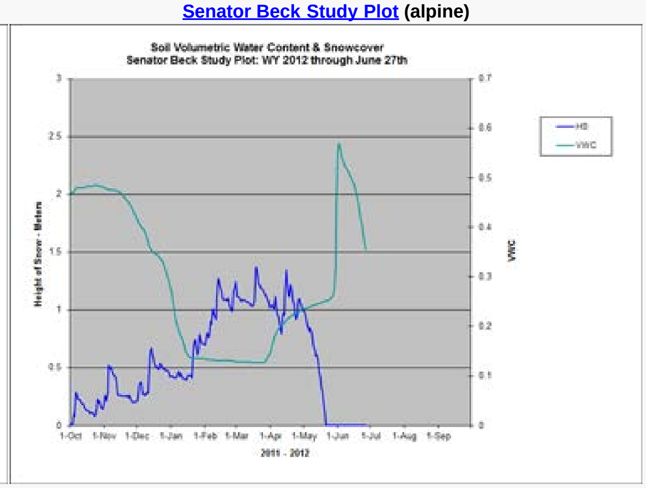


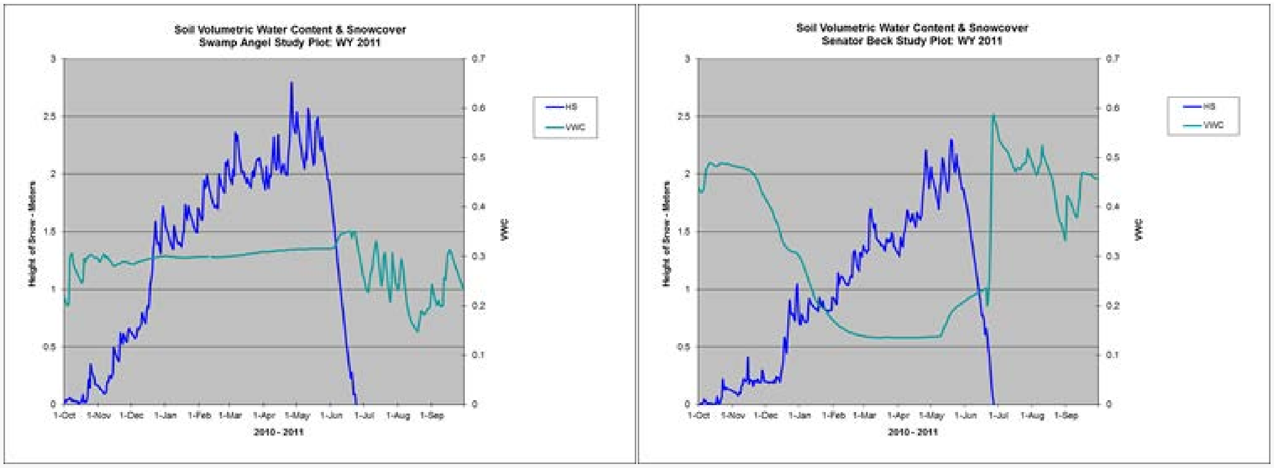
Dust-on-snow frequently produces additional roughness at the snowpack surface that may enhance both sublimation and evaporation of ice and free water. In this photo, taken May 28th, 2012 near Senator Beck Study Plot, several inches of vertical relief exists in this surface and aggregated clumps of dust can be seen in the tips of the complex ice matrices comprising those formations. Free water is present within the matrix, and the matrix includes voids and gaps where air can pass through and over these ice structures.

Our sense is that this additional dust-induced surface roughness may enhance rates of both sublimation of ice and evaporation of melt water. Unfortunately, those processes and their actual effects on snowmelt runoff yields are extremely difficult to monitor in the field and CSAS does not now have the resources to support the very challenging snowmelt modeling required to better understand these effects, using Senator Beck Basin data and observations.

Similarly, soil moisture conditions are also understood to influence snowmelt runoff yields, particularly antecedent, fall conditions. Soil moisture (volumetric water content, or VWC) at 4" below the surface, soil heat flux at the surface, and soil temperatures at several depths are continuously monitored at both our subalpine Swamp Angel Study Plot (SASP) and our alpine Senator Beck Study Plot (SBSP) in Senator Beck Basin. While several years of data from SASP do show significant VWC carryover from fall to spring, our SBSP data show significant losses of fall VWC during early winter. These two study sites have very different soil characteristics that are generally representative of alpine and subalpine soils at Senator Beck Basin, with deep, gravelly soil at SASP compared to very shallow soil at SBSP. Colorado generally exhibits cold and shallow "continental" snowpacks, versus the warmer and deeper maritime and intermountain snowpacks to our west. Because SBSP is in an exposed alpine tundra location, wind effects often result in an even thinner snowpack at SBSP and in the surrounding alpine terrain than at the well-sheltered, SASP site and its surrounding subalpine terrain.

Soil Volumetric Water Content (at 10cm below soil surface) and Snowpack

Water Year	Swamp Angel Study Plot (subalpine)	Senator Beck Study Plot (alpine)
WY 2012 (in progress) Oct 1, 2011 - June 27, 2012		
WY 2011 Oct 1, 2010 - Sept 30, 2011		



Soil volumetric water content (VWC), measured 4” below the soil surface, and snowpack depth are shown for the subalpine Swamp Angel Study Plot and alpine Senator Beck Study Plot for Water Years 2011 (complete) and 2012 (in progress). Note the rapid drying of soils at both sites in early summer 2012. See snowstudies.org/data/graphs/soil_VWC_snowpack.html to view data for all years since 2006.

Deeper soil at SASP may retain a large reservoir of moisture that replenishes near-surface VWC during early winter, counteracting the water vapor pressure gradient drawing vapor from the relatively warmer soil into the colder snowpack. As the snowpack approaches a meter in depth, stabilizing the soil/snowpack temperature gradient, that vapor pressure gradient also stabilizes leaving substantial VWC in near-surface soil. In contrast, our sense is that the comparatively small reservoir of moisture in the much thinner alpine soils at SBSP is being depleted, and cannot sustain VWC in near-surface soils during fall and early winter. Strong water vapor pressure gradients draw moisture from the warmer soil to the snowpack until the snowpack there also approaches a depth of a meter or more.

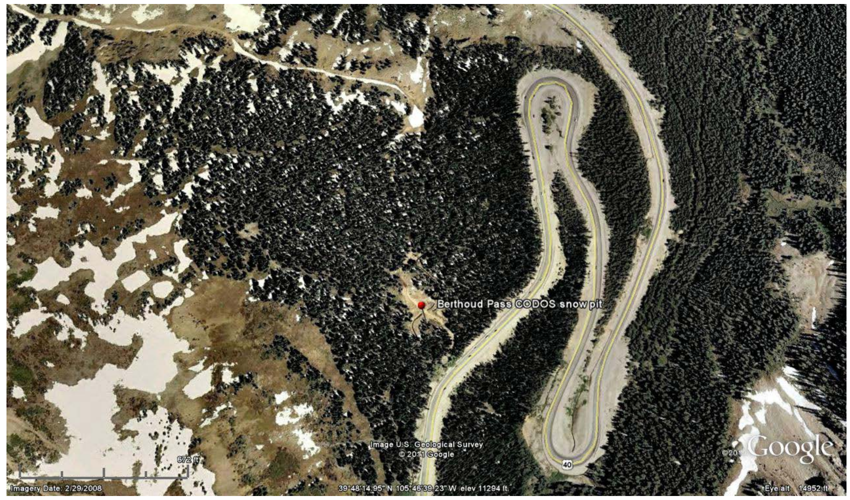
Curiously, VWC at SBSP also shows some rebound in late winter, during snowpack, that is not occurring at SASP. We do not understand that difference. SBSP also shows a significant increase in VWC at snow all gone that is not matched at SASP. That surge is clearly related to short term sheet flow and pooling of snowmelt water during final melting around SBSP. Because Colorado has a high elevation mountain system, with a substantial proportion of SWE accumulation on thin soils above treeline, these consistent differences in VWC carryover behavior may be important to understanding and forecasting alpine snowpack snowmelt yields.

Finally, as discussed above, the last two winter seasons took place under back-to-back La Niña conditions. Does a relationship exist between ENSO states, or other hemispheric-scale climatic drivers, and the kinds of synoptic-scale wind field formation that favors dust mobilization and emission from the Colorado Plateau exist, and could this be a predictive parameter of wind field characteristics favoring or disfavoring dust storms in Colorado? Our history of rigorous dust-on-snow deposition and wind monitoring at Senator Beck Basin is still short, but perhaps sufficient to begin exploring that question with researchers interested in the climatology of wind in the western US, and how regional climate change might alter wind behavior and desert dust emissions.

CENTER FOR SNOW & AVALANCHE STUDIES

WATER YEAR 2012 CODOS SUMMARY FOR BERTHOUD SUMMIT

Summary | Snowpack & Dust | Melt Rates | Stream Flows



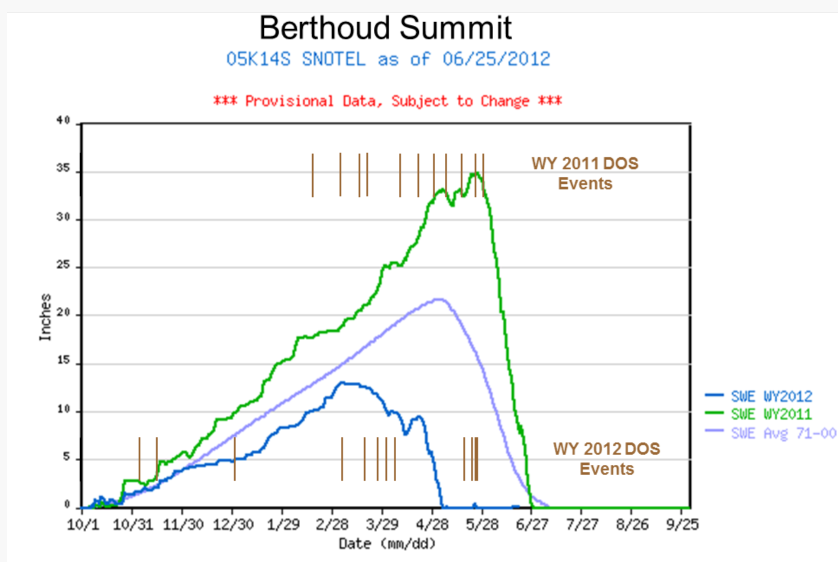
SUMMARY

Water Years 2011 and 2012 produced a case study in interannual variability of Colorado snowpack formation and ablation driven by vastly different late winter and spring conditions, perhaps representing seasonal extremes. On the other hand, overall, the two seasons produced *comparatively* similar dust-on-snow conditions in the Colorado mountains. Unusually sustained, stormy winter weather in spring 2011 resulted in relentless snowfalls postponing sustained dust-on-snow effects until very late into the season, in early June. Dust did eventually enhance high runoff rates from historically large or, at some locations in the northern mountains, record-breaking snowpacks.

In dramatic contrast to WY 2011, extremely dry late-winter and spring weather conditions in 2012 resulted in very low values of peak SWE and an unusually early and dust-enhanced start to snowpack ablation. Beginning in March, dust-on-snow layers remained exposed at the snowpack surface for prolonged periods, absorbing enough additional solar energy to initiate and enhance snowmelt and runoff well in advance of long-term average timing. In conjunction with sub-par snowpacks, this dust-enhanced radiative forcing then generated a well-below-normal peak in snowmelt runoff well ahead of normal timing, followed by a rapid decline in runoff flows in June to levels normally observed in late summer.

SNOWPACK & DUST

Water Year 2012 snowpack formation at the Berthoud Summit Snotel began at near-average rates in early winter before slipping into the lower quartile of cumulative SWE values by mid-winter (see Snotel projection plot below). Due to the very dry late-winter and spring experienced throughout Colorado, WY 2012 peak SWE, at only 13.0", fell far short of the 1971-2000 average of 21.7". Peak SWE also occurred very early in the season, on March 6th, nearly two months earlier than the 1971-2000 average date of peak SWE of May 3rd and fully 81 days earlier than the extremely late date of peak SWE during WY 2011. Further, WY 2012 "snow all gone" (SAG) at Berthoud Summit occurred three weeks *before* the date of peak SWE in WY 2011.



Berthoud Summit Snotel SWE accumulation and ablation for Water Years 2011 and 2012, with dust-on-snow events shown, by date, as brown bars for both water years (as observed at the Senator Beck Basin Study Area).

The total number of dust-on-snow events in WYs 2011 and 2012 (at 11 and 12, respectively) and their total mass of dust loading (at 14 and ~10-12 grams per square meter) were similar (see the Senator Beck Basin dust log discussion). Despite those similarities, diametrically different late winter and spring weather during the past two seasons resulted in dust having very different effects on snowmelt processes at Berthoud Summit and throughout the State.

Eleven dust events occurred at Senator Beck Basin in the late winter and spring of 2011, many of which were confirmed in the Front Range. However, relentless accumulation of late winter and spring snow buried new dust layers and frequently restored high snow albedo values, until the end of May. That sustained winter-like weather also added to and conserved the substantial snowpack cold content measured in our March 31st, 2011 snowpit at Berthoud Summit. Subsequently, prior to our April 24th, 2011 snowpit that snowpack had become isothermal. Eventually, on May 29th, 2011 the final and perhaps largest dust event of the season was deposited on the surface of what was effectively Peak SWE and sustained sunny weather replaced the stormy regime. Rapid snowmelt began immediately and dust layers quickly merged and remained fully exposed to maximum rates of incoming radiation, as the summer solstice approached.

Because late winter and spring 2012 were exceptionally dry, with widely spaced and comparatively small winter storms **(**see the Senator Beck Basin winter storm discussion), dust-on-snow event D4-WY2012 on March 6th and subsequent dust events that merged with and enhanced D4 were only occasionally and briefly buried under clean new snow. Although dust loading and reductions in snow albedo at Berthoud Summit were somewhat less intense than at the Senator Beck Basin Study Area, the reduction in snow albedo was sufficient, over the extended periods of dust exposure to incoming radiation, to result in advancing the rate of snowpack warming to 0° C throughout. Then, once isothermal, all additional energy absorbed by dust at the snowpack surface resulted in enhanced rates of snowmelt and snowpack ablation.

Since snowcover ablation at Berthoud Summit began in early April or May, mean air temperature over the entire snowmelt period, to SAG, was comparatively cool, despite episodes of unseasonably warm weather (see table below). Nonetheless, given the minimal snowpack, and the sustained periods of dry, sunny weather supporting the dust-enhanced radiative forcing of snowmelt, the Berthoud Summit Snotel recorded the earliest date of SAG in its period of record, even before the final four dust events of the season could further lower snow albedo. Those later dust events did nonetheless fall onto and further reduce snow albedo on the remaining higher elevation, alpine snowcover in the Berthoud Pass locale.

MELT RATES

Berthoud Summit Snotel Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Period Add Precip	Period Mean Temp C	Adjusted Daily Mean Loss SWE	Maximum 5-Day Moving Average of Daily Loss of SWE
WY 2006	4/21/2006	24.0	41	3.8	3.5	0.68	1.48
WY 2007	4/27/2007	22.2	46	4.5	4.4	0.58	0.92
WY 2008	5/16/2008	24.4	34	1.4	5.8	0.76	1.14
WY 2009	4/20/2009	24.7	50	5.2	4.0	0.60	1.34
WY 2010	5/16/2010	24.5	23	0.6	6.6	1.09	1.62
WY 2011	5/26/2011	34.8	35	2.0	8.4	1.05	1.46
WY 2012	3/6/2012	13.0	60	3.2	1.4	0.27	1.14
Max	05/26/11	34.8	60	5.2	8.4	1.1	1.6
Min	03/06/12	13.0	23	0.6	1.4	0.3	0.9
Range	81	21.8	37	4.6	7.0	0.8	0.7
Median		24.4	41	3.2	4.4	0.7	1.3

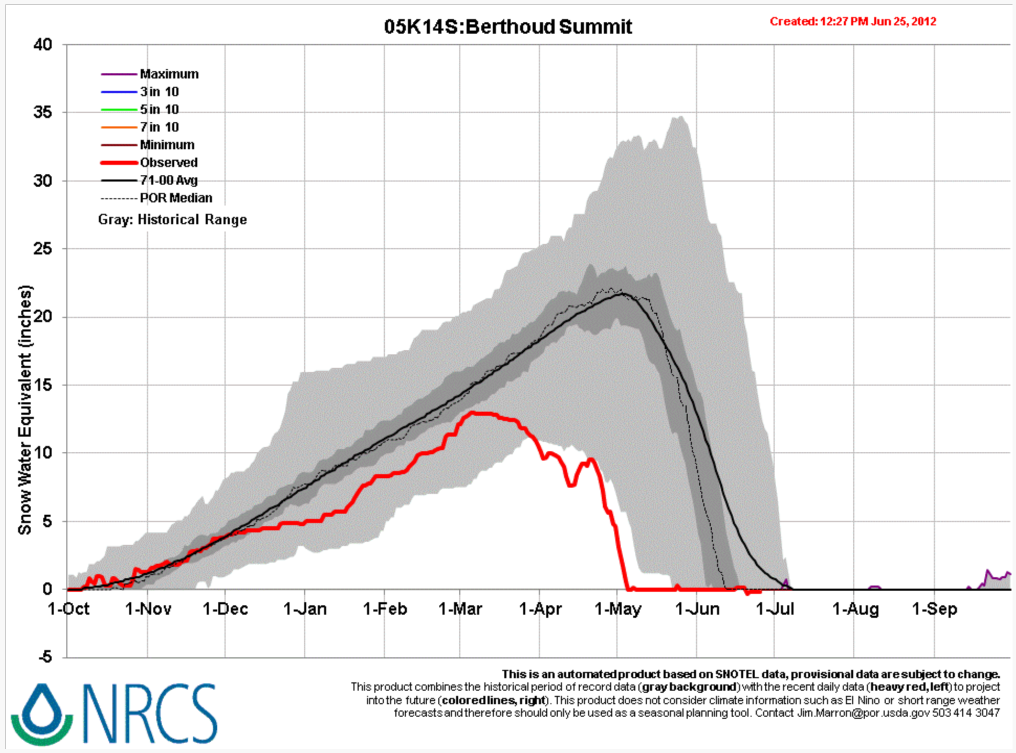
Analysis of Berthoud Summit Snotel data for 2006-2012 snowmelt seasons showing date and quantity of peak SWE, days from peak SWE to "snow all gone" (SAG), total additional precipitation after date of peak SWE, an "adjusted" mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG.

This discussion references CODOS Snotel site data and analyzes rates of snowmelt from Spring 2006 to the present, spanning the period during which we've rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. As discussed in prior CODOS Updates, Snotel sites typically exhibit a radiative regime where surrounding trees reduce the access of incoming solar radiation to snowcover over the SWE measuring snow pillow, and where re-radiation of long wave energy from that vegetation and reduced skyview may sustain periods of surface snowmelt during nighttime hours. Therefore, Snotel sites are not an ideal site for monitoring the maximum effects of dust-on-snow on snowmelt timing and rates, as compared to generally level, open meadow sites where solar access is unimpeded and snowmelt energy budgets and snowpack ablation are measured. Nonetheless, the Snotel network is the only spatially extensive system monitoring snowmelt throughout the Colorado mountains and year-to-year comparisons of Snotel melt rate data may yield insights into dust effects on local watershed-scale processes.

Berthoud Summit is an exception to the rule. The open, unshaded location of the Berthoud Summit Snotel, in an east-facing clearing just a few yards from our CODOS snowpit site, does afford nearly full solar access to the snowcover over the snow pillow. As a result, the influence of dust on melt rates at this Snotel site is more similar to nearby open terrain than at most Snotel sites.

During WY 2012, three fall and early winter dust storms were observed at Senator Beck Basin and were found low in the snowpack there and at other CODOS sites. While early season dust can result in loss of early season snowcover at lower elevations and on south aspects, those three early events played only a small role in spring snowmelt, where they were still present. And, although several dust-on-snow events fell after the date of SAG at our Senator Beck Basin Study Area and many Snotel sites in WY 2012, those later events did nonetheless further reduce snow albedo on the remaining snowpack at higher elevations and on shady aspects in the nearby terrain.

Perhaps largely because of the very early date of Peak SWE, on March 6th, spring 2012 produced two distinct periods of snowmelt behavior at Berthoud Summit, each with substantially different rates of SWE loss. As seen in the table above for the 2006-2012 period, Spring 2012 produced the lowest value and earliest date of Peak SWE in the past seven years yet still required the most days to fully ablate the snowcover (60), at the lowest rate of daily SWE loss (0.27" per day) for the full snowmelt period.



WY 2012 SWE accumulation and ablation at Berthoud Summit snotel, with upper and lower quartiles of period of record shown in light grey, middle quartiles in dark grey surrounding median trace for period of record, and mean trace for 1971-2000 period.

The avove plot of Berthoud Summit Snotel data shows a slowly accelerating rate of snowpack ablation in March, 2012, as a combined effect of the lack of precipitation and early snowmelt behavior enhanced by dust. Short wave solar radiation absorbed by dust layer D4-WY2012, deposited March 6th, had already produced melt-freeze several cycles in the snowpack surface by the time we conducted our March 15th, 2012 snowpit at Berthoud Summit, with melt energy percolating downward from the snow surface and incrementally warming the still-cold snowpack toward isothermal.

However, this infiltration of melt (free water) energy into the snowpack began early in March. Clear nights in March would have resulted in considerable radiant cooling of the snowpack's near-surface layers, offsetting daytime warming from percolating melt water on some days (overnight cloud cover would minimize that radiant cooling offset). No measured data are available at this site to support that scenario, but these processes are well understood and documented elements of the annual snowmelt energy budget. Very small precipitation events in late March may have also restored somewhat higher snow albedo values for brief periods.

Eventually, as a combined result of surface energy inputs, enhanced by dust, and geothermal heating from the ground below, our April 10, 2012 snowpit revealed a fully isothermal snowpack composed of "very wet" snow throughout, with dust layers D8-D4 merged at the surface. In Spring 2011, the snowpack retained considerable cold content on March 31st but was fully isothermal by April 24th. Given the substantially larger amount of total ice mass to warm to 0° C in 2011, compared to Spring 2012, perhaps the prolonged exposure of dust in March 2012 was the determining factor in producing an isothermal snowpack by April 10, 2012, two weeks earlier than in 2011, despite considerably more clear nights in March and early April 2012 than in March and early April 2011. Melt rates for the first part of the 2012 snowmelt season, from March 6th to April 13th, averaged just 0.15" SWE per day, but were as high 0.7" on April 11th and 12th

A period of unsettled weather beginning April 12th, 2012 produced a rebound in snowpack SWE, adding 2.2" of SWE back to the snowpack by April 20th. Following this stormy interlude, snowpack ablation resumed on April 21st and was complete to SAG (snow all gone) by May 5th, losing 9.5" of SWE in 15 days, an average rate of 0.63" SWE per day. The final five days of snowcover melted at an average rate of 1.14" per day. Within our period of analysis, these are low rates of melt, and the average of 0.27" of SWE loss per day over the entire 60 days of snowmelt is the lowest daily rate by a wide margin.

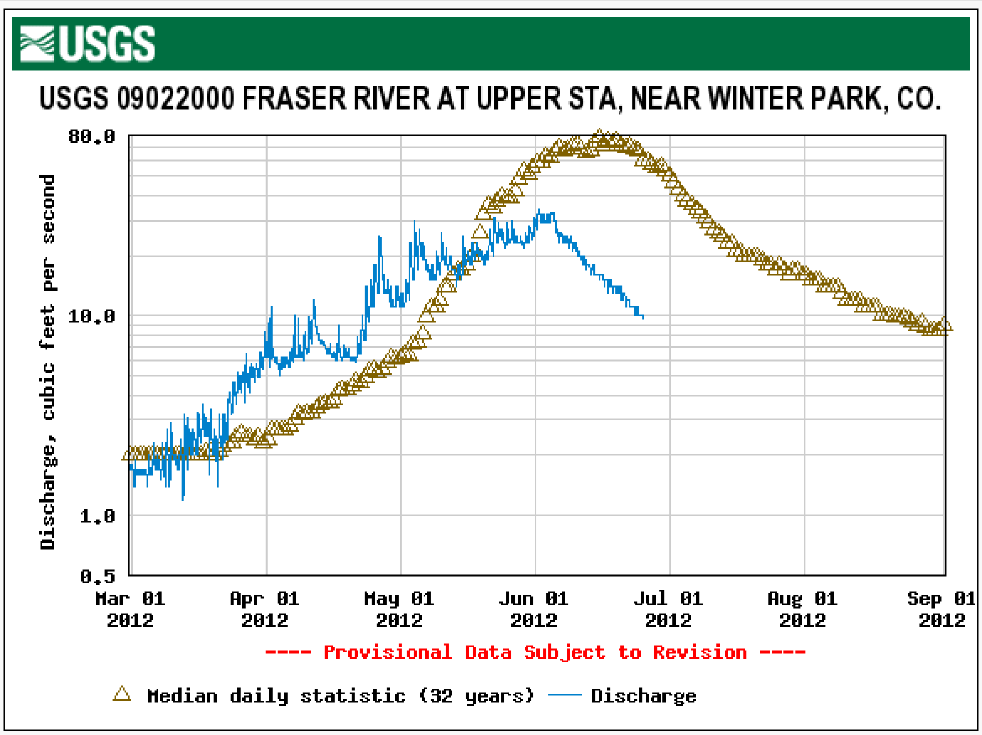
In contrast to the very early snowmelt season of 2012, the prior Spring of 2011, with its very late snowmelt season, produced among the highest rates of average daily SWE loss in our 2006-2012 period of analysis and quicker times to SAG, despite the largest total of SWE to melt. Spring 2010 produced the highest single-day and 5-day rates of SWE loss and shortest interval from Peak SWE to SAG, starting in mid-May.

May 26, **2010** June 9, **2011** May 2, **2012**

Photos in 2010, 2011, and 2012 at the Berthoud Summit CODOS snowpit site showing the snowpack surface late in the snowmelt season, with all/most dust layers merged at the surface, show clear differences in dust loading and reduction of snow albedo, with the least reduction in 2012.

STREAM FLOWS

Streamflow data at the USGS Fraser River at Upper Station gauge reflect an early and reduced snowmelt runoff. Streamflows on the ascending limb, in late March and throughout April, were several times average discharge levels for that period until intersecting with the median trace in early May, near 30 cfs, and then falling behind median rates. A final surge produced a peak just over 30 cfs in early June, at roughly 50% of median discharge for that date, followed by a steep decline that has already approached flow levels normally seen in mid-August. Overall, this hydrograph presents a substantial advance in the timing of WY 2012 runoff, with the center of the reduced runoff mass occurring several weeks earlier than normal.



WY 2012 USGS Fraser River near Winter Park Stream Gauge data for a 10.5 sq. mi. drainage area in the upper Fraser River watershed, above 9,520'. Current year and historic data reflect withdrawals for a transmountain diversion through the Berthoud Pass ditch to West Fork Clear Creek basin.

WATER YEAR 2012 CODOS SUMMARY FOR GRAND MESA

Summary | Snowpack | Melt Rate | Stream Flows

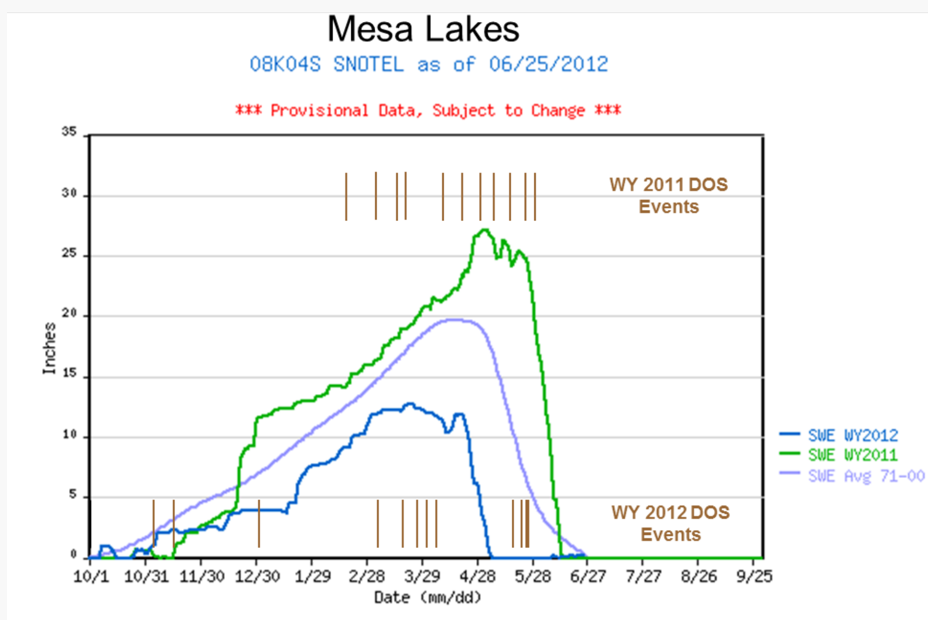
SUMMARY

Water Years 2011 and 2012 are a case study in interannual variability of Colorado snowpack formation and ablation driven by vastly different late winter and spring weather conditions, perhaps representing seasonal extremes. In dramatic contrast with the unrelenting storms of Mar/Apr/May 2011, extremely dry late-winter and spring weather in 2012 resulted in low values of peak SWE, very early in the spring.

On the other hand, the past two seasons produced comparatively smaller differences in dust-on-snow conditions, with WY 2012 coming close to matching WY 2011 at the Senator Beck Basin Study Area, our baseline monitoring site. WY 2012 desert dust concentrations on the Grand Mesa were comparable to those observed at Senator Beck Basin. Spring 2012 snowpack “ripening” was enhanced by those reductions in snow albedo in the first phase of the snowmelt season. The Grand Mesa CODOS site snowpack became isothermal in late March, as snowpack SWE peaked, with several dust layers merged at the snowpack surface. Stormy weather in mid-April produced a small rebound in SWE but then snowmelt rates at the Mesa Lakes Snotel site subsequently accelerated sharply, to a record early date of “snow all gone” (SAG). Streamflow data from the nearby USGS Plateau Creek and Surface Creek gauges document a substantial advance in the snowmelt runoff cycle.

SNOWPACK & DUST DISCUSSION

Water Year 2012 snowpack formation at Grand Mesa and the Mesa Lakes Snotel began well but, after Thanksgiving, SWE accumulations then began to slip quickly into and almost below the lower quartile of daily SWE values (see Snotel projection plot below). A rebound in SWE in mid-January assured that SWE values would remain within that lower quartile for the duration of the season, until SAG. Peak SWE arrived at the Mesa Lakes Snotel very early, on March 24th, at just 12.7”, well short of the 1971-2000 average of 19.7” and more than three weeks earlier than the April 16th average date of peak SWE. Peak SWE in 2011 was over double that of 2012, at 27.1” of water content, and occurred on May 4th, almost three weeks later than average.

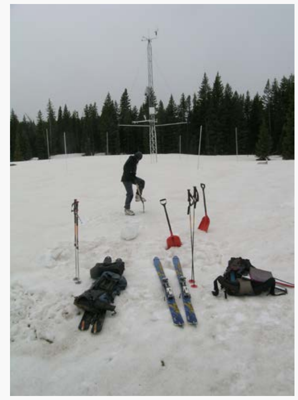


SWE accumulation and ablation for Water Years 2011 and 2012, with dust-on-snow events shown, by date, as brown bars for both water years (as observed at the Senator Beck Basin Study Area).

During WY 2011 eleven dust events occurred at Senator Beck Basin containing a total of 14 grams of dust per square meter. Most of those major dust layers were found in CODOS snow profiles that season at the Grand Mesa CODOS site. However, relentless accumulation of late winter and spring snow routinely buried new dust layers and restored high snow albedo values throughout April and May, until the final and perhaps largest event of the season on May 29th.

Last season, during WY 2012, a similar twelve dust events occurred at Senator Beck Basin containing a total of ~10-12 grams of dust per square meter (see Senator Beck Basin Summary – Dust Log discussion). But, in a dramatic switch, late winter and spring 2012 were exceptionally dry, with widely spaced and comparatively small winter storms (see Senator Beck Basin – Winter Storm Log Discussion) leaving dust exposed at the snowpack surface for extended periods, beginning in early March.

In our March 16th snow profile at our Grand Mesa CODOS site at the Skyway ski trail system, at 10,630', we found event D4 dust at the surface of the 146 cm (57") snowpack, with 12 cm of very wet melt/freeze polycrystals at the snowpack surface. The snowpack was already quite warm, retaining minimal cold content, with a mean snowpack temperature of -0.3° C. Total SWE in our CODOS site snowpit was 509 mm (20.0"), versus just 12.2" at the Mesa Lakes Snotel site. The Mesa Lakes Snotel is the nearest Snotel to our CODOS site, 2 miles to the west but 630' lower in elevation, at 10,000'.



CSAS's Kim Buck starting the May 1st CODOS snow profile at the Grand Mesa site. Very tough ice layers often require using a steel 'sod spade' to begin the snowpit, as Kim is doing here. Our gear is sitting over the location of our prior two snowpits at this site. With each snowpit we move a little closer toward the tower, assuring that our time series of profiles over a given spring are minimally affected by local spatial variations in snowpack properties caused by wind effects, or by the preceding snowpit.

Our next snow profile at the Grand Mesa CODOS site was performed on April 4th to coincide with snow surveys being performed by State and local officials. That day we found the 124 cm (49") snowpack effectively isothermal at 0° C, with wet snow forms throughout the entire depth. Merged dust layers coinciding with events D4-D6 were just below the snowpack surface, thinly covered with an inch of rapidly melting new snow containing dust event D7, which fell April 1st. Total snowpack SWE was virtually unchanged, at 504 mm (19.8"), but a storm just after our prior snowpit had added at least 0.5" of SWE to the snowpack, indicating that some SWE had been recently lost (as the very wet snowpack also indicated).

Following a period of unsettled weather in mid- and late-April, we performed our final CODOS site snow profile of the season on May 1st. The snowpack remained isothermal and still 82 cm (32") deep, containing 325 mm (12.8") of SWE. Dust layers D4-D8 had merged and were substantially reducing snow albedo at the snowpack surface to ~0.52-0.55 (52-55% reflectance). The Mesa Lakes Snotel site would experience SAG just five days later, on May 6th, and the Grand Mesa CODOS site recorded SAG on/about May 15th.

MELT RATE

Mesa Lakes Snotel Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Period Add Precip	Period Mean Temp C	Adjusted Daily Mean Loss SWE	Maximum 5-Day Moving Average of Daily Loss of SWE
WY 2006	4/8/2006	17.9	39	1.6	3.8	0.50	0.88
WY 2007	4/14/2007	13.0	31	3.1	3.3	0.52	1.14
WY 2008	4/12/2008	23.3	59	5.3	3.1	0.48	1.20
WY 2009	4/18/2009	19.2	32	2.5	5.0	0.68	1.42
WY 2010	4/9/2010	16.9	51	5.0	2.9	0.43	0.92
WY 2011	5/4/2011	27.1	41	4.0	5.8	0.76	1.52
WY 2012	3/24/2012	12.7	43	2.1	3.4	0.34	0.98
Max	05/04/11	27.1	59	5.3	5.8	0.8	1.5
Min	03/24/11	12.7	31	1.6	2.9	0.3	0.9
Range		14.4	28	3.7	2.9	0.4	0.6
Median		17.9	41	3.1	3.4	0.5	1.1

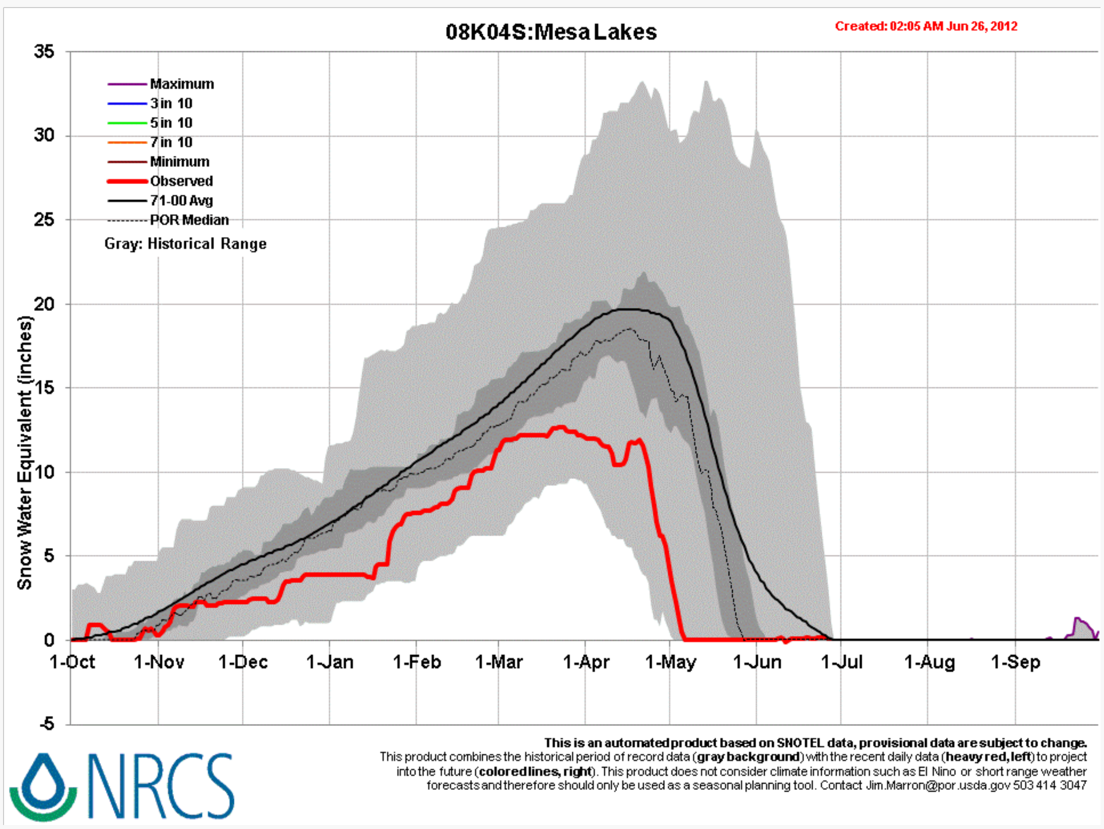
Analysis of Mesa Lakes Snotel data for 2006-2012 snowmelt seasons showing date and quantity of peak SWE, days from peak SWE to "snow all gone" (SAG), total additional precipitation after date of peak SWE, an "adjusted" mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG.

This discussion references CODOS Snotel site data and analyzes rates of snowmelt from Spring 2006 to the present, spanning the period during which we've rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. Since the Snotel network is the only spatially extensive system continuously monitoring snowmelt throughout the Colorado mountains, year-to-year comparisons of Snotel melt rate data may yield insights into dust effects on local watershed-scale processes that our occasional CODOS snowpit measurements can't reveal.

However, as we often note, many Snotel sites exhibit a radiative regime where surrounding trees reduce the access of incoming solar radiation to snowpack over the SWE measuring snow pillow, and where re-radiation of long wave energy from that vegetation and reduced skyview may inhibit radiant cooling and extend surface snowmelt during nighttime hours. Forest cover around the Mesa Lakes Snotel site is set back and, as a consequence, this site may come closer to experiencing the maximum effects of dust reductions in snow albedo, and snowmelt forcing, that we observe at our CODOS Grand Mesa snowpit site, where solar access is unimpeded.

A view of the Mesa Lakes Snotel site, courtesy of NRCS (from the Mesa Lakes Snotel web page).

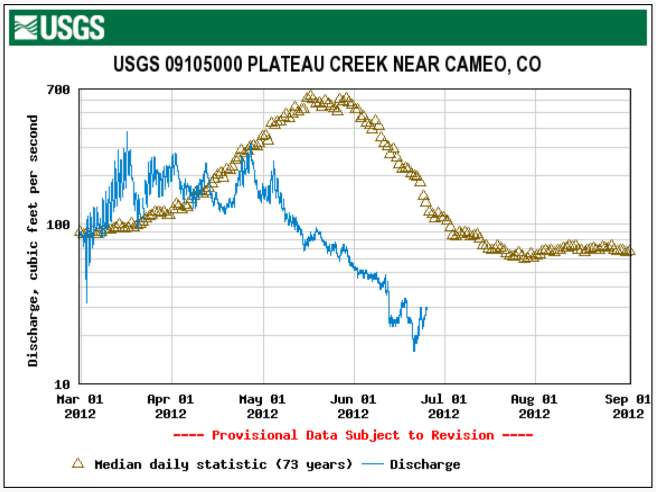
During WY 2012, three fall and early winter dust storms were observed low in the snowpack at Senator Beck Basin, and D1 and D3 were also discernible at Grand Mesa in our CODOS snow profiles. Later, dust-on-snow events D9-D12, from May 18th-26th, may have had little effect on the Grand Mesa snowmelt cycle, as very little snowpack was left in open terrain at these sub-alpine elevations (the CODOS site was SAG on May 15th).



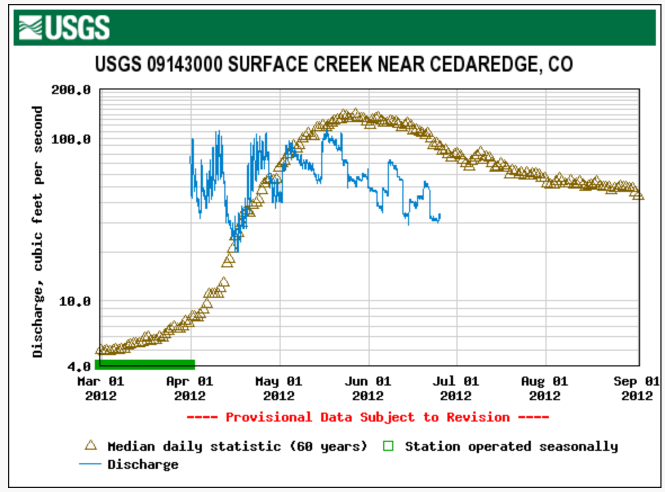
WY 2012 SWE accumulation and ablation at Mesa Lakes Snotel with upper and lower quartiles of period of record shown in light grey, middle quartiles in dark grey surrounding median trace for period of record, and mean trace for 1971-2000 period.

Even with the early date of WY 2012 peak SWE at Mesa Lakes Snotel, on March 24th, spring 2012 produced a two-step descending limb in the SWE plot similar to the pattern after peak SWE in 2011. In 2012, snowpack ablation gradually accelerated in mid-March until storms in mid-April produced a small rebound in SWE. Then, in late April, under the influence of unseasonably warm temperatures and further reductions in snow albedo from dust, melt rates accelerated again and remained high. Overall, the Mesa Lakes Snotel site required 43 days to ablate 14.8" of SWE (including 2.1" of precipitation after peak SWE), averaging 0.34" of SWE loss per day. However, the final, sustained meltdown from April 20th, at almost 12" of SWE, to SAG on May 6th required just 17 days, averaging a rate of 0.7" SWE loss per day and reaching 1.2" of loss on some days.

STREAM FLOWS



WY 2012 USGS Plateau Creek near Cameo stream gauge data for a 592 sq. mi. drainage area, largely on northern aspects of Grand Mesa, above 4,840'. Natural flow of the stream is affected by storage reservoirs, diversions for irrigation of about 25,000 acres, return flow from irrigated areas, and diversions for power development.



WY 2012 USGS Surface Creek near Cedaredge stream gauge data for a 27 sq. mi. drainage area on southern aspects of Grand Mesa, above 8,261'. Flow is regulated by many small reservoirs. Some water is imported from Leon Lake in the Plateau Creek drainage.

Given the very dry winter and sub-par snowpack on Grand Mesa, below average snowmelt runoff was unsurprising. However, in response to periods of dry, sunny, unseasonably warm weather and sustained exposure of significant dust-on-snow, spring 2012 snowmelt runoff hydrographs also exhibited early onset at unusually high rates, with a corresponding early and steep descending limb.

Although the Surface Creek gauge only began measurements in early April, with flows well underway, both of the above hydrographs show an early start to runoff with substantially above-average flows in Plateau Creek in March and in Surface Creek in April. Then, flows began a steep decline in early May. Flow management thereafter complicates further interpretation of these hydrographs, but flows clearly continued to decline.

In addition to the very warm temperatures associated with prolonged periods of dry and sunny weather in late winter and spring 2012, dust-on-snow events D4 (March 6th) through D8 (April 6th) played a significant role in this early Grand Mesa runoff, reducing snow albedo and hastening the ripening of the snowpack in late March, to isothermal. Dust then continued absorbing and adding solar energy to the snowmelt energy budget during subsequent periods of exposure at the snowpack surface in April and May. Because of the very early dates of SAG at the Mesa Lakes Snotel and at our Grand Mesa CODOS site, subsequent dust events D9-D12, in late May, fell on mostly bare ground in open terrain, with snowpack limited to forested areas, and played little role in late snowmelt behavior. Had late winter of 2011/2012 been more normal, with peak SWE and snowpack ablation following the mean or median timing seen in the Snotel plot above, those late-May dust events could have fallen onto more substantial remaining snowpack and played a significant role in the final stages of snowmelt, as occurred in spring 2011.

[CODOS Water Year 2012 Updates](#) > [2012 Summary](#) > Grizzly Peak

WATER YEAR 2012 CODOS SUMMARY FOR GRIZZLY PEAK

Summary | Snowpack | Melt Rate | Stream Flows

SUMMARY

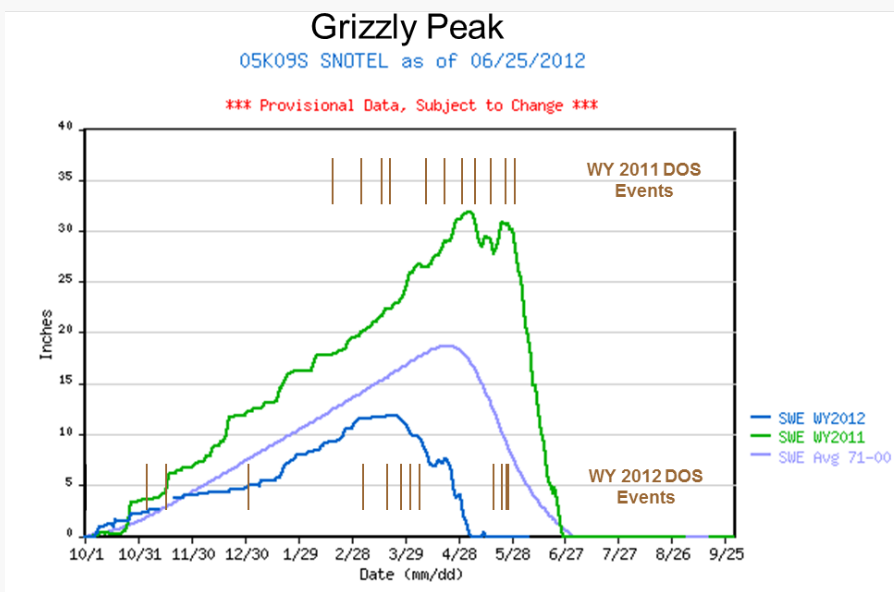
Water Years 2011 and 2012 are a case study in interannual variability of Colorado snowpack formation and ablation driven by vastly different late winter and spring weather conditions, perhaps representing seasonal extremes. In dramatic contrast with the unrelenting storms of Mar/Apr/May 2011, extremely dry late-winter and spring weather in 2012 resulted in low values of peak SWE, very early in the spring.

On the other hand, the past two seasons produced comparatively smaller differences in dust-on-snow conditions, with WY 2012 coming close to matching WY 2011 at the Senator Beck Basin Study Area, our baseline monitoring site. WY 2012 desert dust concentrations in the Loveland Pass and Grizzly Peak Snotel locale were only somewhat less intense than those observed at Senator Beck Basin. Very large areas of bare ground exposed for most of late winter and spring in Front Range mountains, including the Loveland Pass locale, may have also enabled larger amounts of local dust and vegetation debris to mix with desert dust than has occurred in prior seasons. In any event, whether because of desert or local dust, or both, spring 2012 snowpack warming was enhanced by minor reductions in snow albedo and the Grizzly Peak CODOS site snowpack became isothermal sometime in late March or early April. On April 10th the site was rapidly approaching “snow all gone” (SAG) with several dust layers merged at the snowpack surface. Streamflow data from the nearby USGS Snake River near Montezuma gauge document a substantial advance in snowmelt timing.

SNOWPACK & DUST DISCUSSION

Water Year 2012 snowpack formation at the Grizzly Peak Snotel site began well but by early December had fallen well behind average accumulations into the lower quartile of SWE values for the period of record (see [Snotel projection plot below](#)). After rebounding just into the second quartile in mid-winter, peak SWE occurred very early, on March 22nd, at just 11.9”, well short of the 1971-2000 average of 18.6” and a full month earlier than the April 22nd average date of peak SWE. Peak SWE in 2011 was 31.8” and occurred on May 5th.

During WY 2011 eleven dust events occurred at Senator Beck Basin containing a total of 14 grams of dust per square meter. Most of those major dust layers were found in CODOS snow profiles that season at the Grizzly Peak CODOS site. However, relentless accumulation of late winter and spring snow routinely buried new dust layers and restored high snow albedo values throughout April and May, until the final and perhaps largest event of the season on May 29th.



SWE accumulation and ablation for Water Years 2011 and 2012, with dust-on-snow events shown, by date, as brown bars for both water years (as observed at the Senator Beck Basin Study Area).

Last season, during WY 2012, a similar twelve dust events occurred at Senator Beck Basin containing a total of ~10-12 grams of dust per square meter (see Senator Beck Basin Summary – Dust Log discussion). But, in a dramatic switch, late winter and spring 2012 were exceptionally dry, with widely spaced and comparatively small winter storms (see Senator Beck Basin – Winter Storm Log Discussion) leaving dust exposed at the snowpack surface for extended periods, beginning in early March.

In our March 15th snow profile at our Grizzly Peak CODOS site, we found event D4 dust at the surface of the 104 cm (41") snowpack, with a tough melt/freeze crust at the snowpack surface. Despite that recent surface melt, the snowpack retained significant cold content on this date, with a mean snowpack temperature of -4.6° C.

By April 10th, our next snow profile at Grizzly Peak found the diminished 35 cm (14") snowpack isothermal at 0° C and with wet snow throughout, with merged dust layers coinciding with events D8-D4 at the surface. SAG occurred shortly thereafter and, on our final CODOS site visit on May 2nd we hiked the east-facing slope from Hwy 6 to our snow-free CODOS site on dry ground. Several days later in the preceding season, on May 17th, 2011 the snowpack at the Grizzly Peak CODOS site was still 203 cm (80") deep, with fresh snow at the surface and more snow to come later in the month.

The Grizzly Peak CODOS snowpit site on May 2nd, **2012** compared to a year earlier on May 17th, **2011**, with CSAS's Andrew Temple just getting started on the 80" deep snowpit.

MELT RATE

Grizzly Peak Snotel Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Period Add Precip	Period Mean Temp C	Adjusted Daily Mean Loss SWE	Maximum 5-Day Moving Average of Daily Loss of SWE
WY 2006	4/4/2006	21.6	49	3.5	2.3	0.51	1.30
WY 2007	4/20/2007	20.6	43	3.0	3.0	0.55	1.00
WY 2008	4/13/2008	23.0	56	4.8	1.7	0.50	1.32
WY 2009	4/20/2009	21.6	47	5.2	3.7	0.57	1.00
WY 2010	4/9/2010	12.8	50	6.0	1.3	0.38	1.10
WY 2011	5/5/2011	31.8	52	5.8	5.1	0.72	1.38
WY 2012	3/22/2012	11.9	44	2.6	2.4	0.33	0.76
Max	05/05/11	31.8	56	6.0	5.1	0.7	1.4
Min	03/22/12	11.9	43	2.6	1.3	0.3	0.8
Range		19.9	13	3.4	3.9	0.4	0.6
Median		21.6	49	4.8	2.4	0.5	1.1

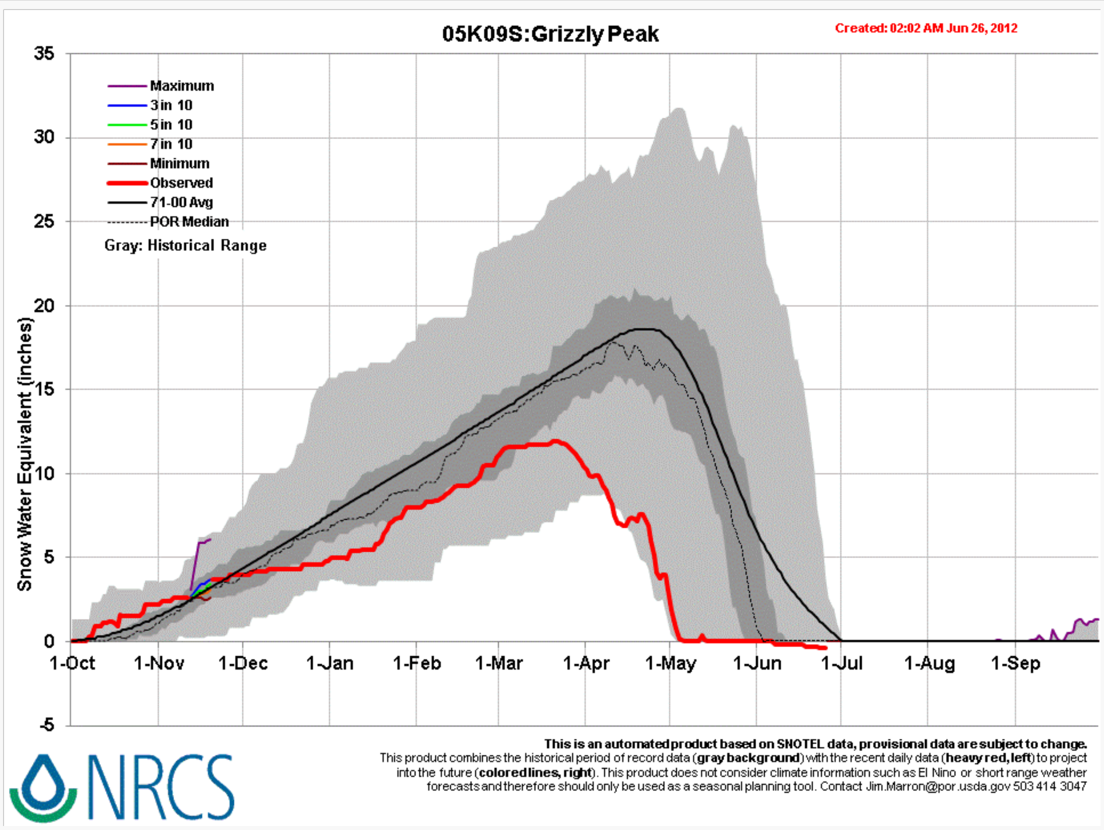
Analysis of Grizzly Peak Snotel data for 2006-2012 snowmelt seasons showing date and quantity of peak SWE, days from peak SWE to "snow all gone" (SAG), total additional precipitation after date of peak SWE, an "adjusted" mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG.

This discussion references CODOS Snotel site data and analyzes rates of snowmelt from Spring 2006 to the present, spanning the period during which we've rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. Since the Snotel network is the only spatially extensive system continuously monitoring snowmelt throughout the Colorado mountains, year-to-year comparisons of Snotel melt rate data may yield insights into dust effects on local watershed-scale processes that our occasional CODOS snowpit measurements can't reveal.

A view of the Grizzly Peak Snotel site approaching SAG on May 2nd, 2012. Although part of the snow pillow can be seen (closest to the camera), 4" of snow containing 1.3" of SWE were still being measured over the remainder of the pillow. Just 200' away, on a generally level and open bench, the Grizzly Peak CODOS snowpit site (see photo above) had been snow-free for some time.

However, as we often note, many Snotel sites exhibit a radiative regime where surrounding trees reduce the access of incoming solar radiation to snowpack over the SWE measuring snow pillow, and where re-radiation of long wave energy from that vegetation and reduced skyview may inhibit radiant cooling and extend surface snowmelt during nighttime hours. The Grizzly Peak Snotel site exhibits these attributes although recent tree removal probably improved solar access somewhat. However, the site is still shaded by trees to the south and, as a consequence, does not experience the maximum effects of dust reductions in snow albedo, and short-wave radiative forcing, as compared to the adjacent open meadow and our CODOS snowpit site where solar access is comparatively unimpeded. This difference in dominant radiation regimes (long-wave in shady forests versus short-wave in sunny, open terrain) is routinely seen where snow-free open meadows immediately adjoin forest retaining snowpack, as was demonstrated at Grizzly Peak on May 2nd, 2012.

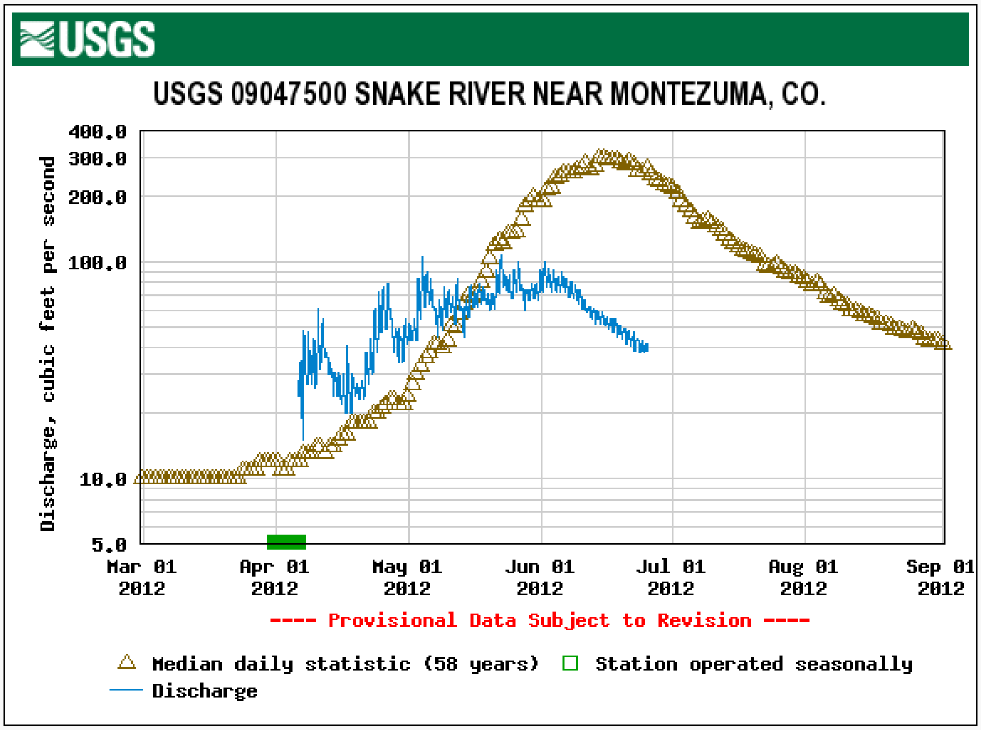
During WY 2012, three fall and early winter dust storms were observed low in the snowpack at Senator Beck Basin, and at least one of these layers (likely D3) was discernible at Grizzly Peak in our CODOS snow profiles. And, although WY 2012 dust-on-snow events D9-D12 fell well after the date of SAG at our Grizzly Peak CODOS site, those later events further reduced snow albedo and enhanced snowmelt rates in the remaining snow cover at higher elevations and on shady subalpine aspects in the nearby terrain.



WY 2012 SWE accumulation and ablation at Grizzly Peak Snotel with upper and lower quartiles of period of record shown in light grey, middle quartiles in dark grey surrounding median trace for period of record, and mean trace for 1971-2000 period.

Because of the early date of WY 2012 peak SWE at Grizzly Peak Snotel, on March 22nd, spring 2012 produced a two-step descending limb in the SWE plot rather than the single, steep plunge following the very delayed peak SWE in 2011. In 2012, snowpack ablation gradually accelerated in early April until storms in mid-April produced a small rebound in SWE. Then, in late April, under the influence of unseasonably warm temperatures and reductions in snow albedo from dust, melt rates accelerated again, to a higher rate. Overall, the Grizzly Peak Snotel site required 44 days to ablate 14.5” of SWE (including 2.6” of precipitation after peak SWE), averaging 0.33” of SWE loss per day.

STREAM FLOWS



WY 2012 USGS Snake River near Montezuma Stream Gauge data for a 58 sq. mi. drainage area in the Snake River watershed, including the North Fork drainage, above 9,320’. Current year and historic data reflect minor diversions upstream for irrigation and domestic use.

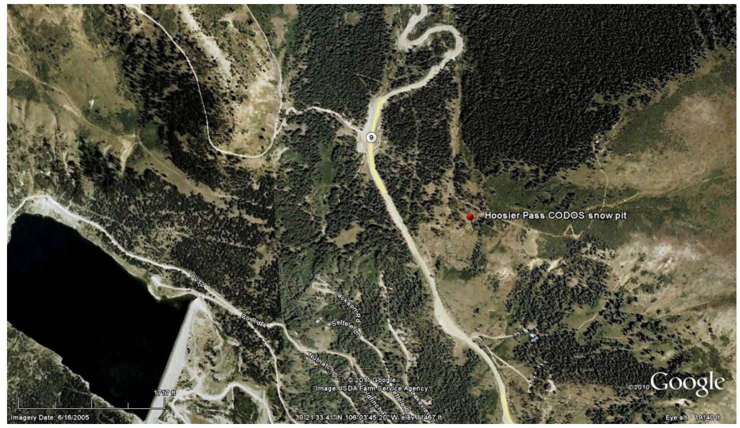
Given the very dry spring and sub-par snowpacks throughout the Front Range mountains, below average snowmelt runoff in those watersheds was unsurprising. The Snake River near Montezuma hydrograph shows evidence of an early start to runoff with substantially above-average flows in April and a peak in early May. Additional surges later in May may have been enhanced by the final four dust-on-snow events of the season. As was typical throughout the state, runoff began a rapid decline in early June and by the end of June streamflows had fallen below those expected two months later, in September.

In addition to the very warm temperatures associated with prolonged periods of dry and sunny weather in late winter and spring 2012, dust-on-snow events D4 (March 6th) and D8 (April 6th) played a role in this early Snake River runoff, reducing snow albedo and hastening the ripening of the snowpack in late March, to isothermal. Dust then continued absorbing and adding solar energy to the snowmelt energy budget during subsequent periods of exposure at the snowpack surface in April and May. Additional dust events in late May, particularly D12 on May 26th, further reduced snow albedo in the scant remaining high elevation snowpack, hastening the extreme drying of Front Range mountain systems.

[CODOS Water Year 2012 Updates](#) > [2012 Summary](#) > Hoosier Pass

WATER YEAR 2012 CODOS SUMMARY FOR HOOSIER PASS

[Summary](#) | [Snowpack](#) | [Melt Rate](#) | [Stream Flows](#)



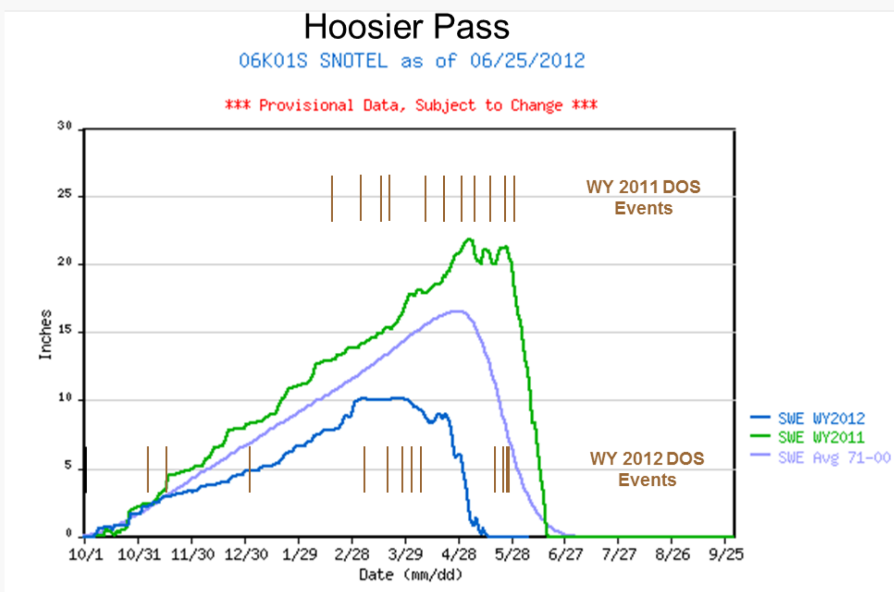
SUMMARY

Water Years 2011 and 2012 are a case study in interannual variability of Colorado snowpack formation and ablation driven by vastly different late winter and spring weather conditions, perhaps representing seasonal extremes. In dramatic contrast with the unrelenting storms of Mar/Apr/May 2011, extremely dry late-winter and spring weather in 2012 resulted in low values of peak SWE, very early in the spring.

On the other hand, the past two seasons produced comparatively smaller differences in dust-on-snow conditions, with WY 2012 coming close to matching WY 2011 at the Senator Beck Basin Study Area, our baseline monitoring site. Locally, however, WY 2012 desert dust concentrations at Hoosier Pass were substantially lower than those observed at Senator Beck Basin. Further, very large areas of bare ground exposed for most of late winter and spring in Front Range mountains, including the Hoosier Pass locale, may have enabled larger amounts of local dust and vegetation debris to mix with desert dust than has occurred in prior seasons. In any event, whether because of desert or local dust, or both, spring 2012 snowpack warming was enhanced by minor reductions in snow albedo and the Hoosier Pass CODOS site snowpack was isothermal by early April, then virtually gone by May 2nd. Streamflow data reflected this advance in snowmelt timing. Flowing north from the Pass, streamflow data from the USGS Blue River near Dillon gauge show an early and substantially reduced snowmelt runoff with rapidly declining flows in June. Southern aspects of the Mosquito Range and other terrain supplying the South Platte River were especially dry, during our CODOS campaigns, and flows measured on Tarryall Creek near Como, into South Park, were also early and extremely low.

SNOWPACK & DUST DISCUSSION

Water Year 2012 snowpack formation at Hoosier Pass began well but steadily fell well behind average accumulations into the lower quartile of SWE values for the period of record (see [projection plot below](#)). After stalling near 10" in early March, peak SWE occurred on March 28th at just 10.2", well short of the 1971-2000 average of 16.5" and a full month earlier than the April 28th average date of peak SWE. (Peak SWE in 2011 was more than double this amount, at 21.9" and occurred on May 5th.)



SWE accumulation and ablation for Water Years 2011 and 2012, with dust-on-snow events shown, by date, as brown bars for both water years (as observed at the Senator Beck Basin Study Area).

During WY 2011 eleven dust events occurred at Senator Beck Basin containing a total of 14 grams of dust per square meter. Most of those major dust layers were found in CODOS snow profiles at the Hoosier Pass CODOS site. However, relentless accumulation of late winter and spring snow routinely buried new dust layers and restored high snow albedo values throughout the State, throughout April and May.

Last season, during WY 2012, a similar twelve dust events occurred at Senator Beck Basin containing a total of ~10-12 grams of dust per square meter ([see Senator Beck Basin Summary – Dust Log](#)

discussion). But, in a dramatic switch, late winter and spring 2012 were exceptionally dry, with widely spaced and comparatively small winter storms (see Senator Beck Basin – Winter Storm Log Discussion) leaving dust exposed at the snowpack surface for extended periods, beginning in early March. However, spring 2012 dust layers and reductions in snow albedo observed in the Hoosier Pass locale were substantially less intense than those observed in the Senator Beck Basin Study Area last spring.

In our March 14th snow profile at our Hoosier Pass CODOS site, we found event D4 dust weakly present at the surface of the 105 cm (41") snowpack, with only a thin melt/freeze crust at the snowpack surface. The snowpack retained significant cold content on this date, with a mean snowpack temperature of -3.7° C. By April 9th, our next snow profile at Hoosier Pass found the 81 cm (32") snowpack isothermal at 0° C and with wet snow throughout. (see April 9 Update). And, for our final CODOS site visit on May 2nd we hiked the west-facing slope from Hwy 9 to our CODOS site on dry ground. Several days later in the preceding season, on May 16th, 2011 the snowpack at the Hoosier Pass CODOS site was still 182 cm (72") deep.

CSAS's Chris Landry returning to Hwy 20 on a gentle, snow-free, west-facing slope after completing the May 2nd, 2012 snowpit at the more level Hoosier Pass CODOS site, just before SAG. Mount Lincoln and Mount Bross are seen in the distance, notably snow-free.

MELT RATE

Hoosier Pass Snotel Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Period Add Precip	Period Mean Temp C	Adjusted Daily Mean Loss SWE	Maximum 5-Day Moving Average of Daily Loss of SWE
WY 2006	4/9/2006	19.3	49	2.7	3.5	0.45	1.06
WY 2007	4/28/2007	18.5	45	3.2	4.2	0.48	0.82
WY 2008	4/15/2008	20.8	61	4.2	2.5	0.41	0.98
WY 2009	4/20/2009	17.3	47	5.3	3.8	0.48	1.08
WY 2010	5/4/2010	14.7	31	1.8	3.3	0.53	1.28
WY 2011	5/5/2011	21.9	44	3.1	4.2	0.57	1.20
WY 2012	3/28/2012	10.2	48	2.9	2.4	0.27	0.90
Max	05/05/11	21.9	61	5.3	4.2	0.6	1.3
Min	03/28/12	10.2	31	1.8	2.4	0.3	0.8
Range		11.7	30	3.5	1.9	0.3	0.5
Median		18.5	47	3.1	3.5	0.5	1.1

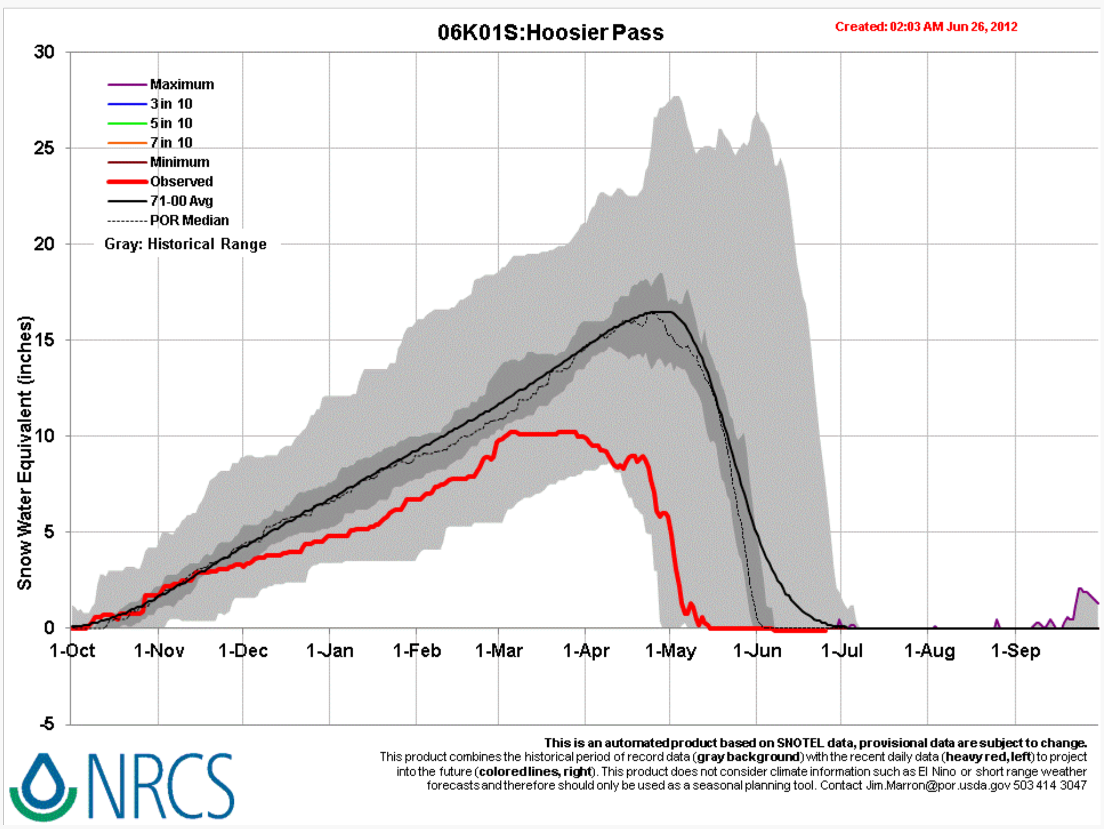
Analysis of Hoosier Pass Snotel data for 2006-2012 snowmelt seasons showing date and quantity of peak SWE, days from peak SWE to "snow all gone" (SAG), total additional precipitation after date of peak SWE, an "adjusted" mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG.

This discussion references CODOS Snotel site data and analyzes rates of snowmelt from Spring 2006 to the present, spanning the period during which we've rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. Since the Snotel network is the only spatially extensive system continuously monitoring snowmelt throughout the Colorado mountains, year-to-year comparisons of Snotel melt rate data may yield insights into dust effects on local watershed-scale processes that our occasional CODOS snowpit measurements can't reveal.

However, as we often note, many Snotel sites exhibit a radiative regime where surrounding trees reduce the access of incoming solar radiation to snowpack over the SWE measuring snow pillow, and where re-radiation of long wave energy from that vegetation and reduced skyview may inhibit radiant cooling and extend surface snowmelt during nighttime hours. The Hoosier Pass Snotel site exhibits these attributes and, as a consequence, does not experience the maximum effects of dust reductions in snow albedo, and short-wave radiative forcing, as compared to open meadow sites where solar access is unimpeded and snowmelt and snowpack ablation are measured (e.g., Swamp Angel Study Plot). This difference in dominant radiation regimes (long-wave in shady forests versus short-wave in sunny, open terrain) is routinely seen where snow-free open meadows immediately adjoin forest retaining substantial snowpack.

A view looking north of the Hoosier Pass Snotel site on April 9th, 2012, showing tree shadows over the snow pillow, inside the fencing.

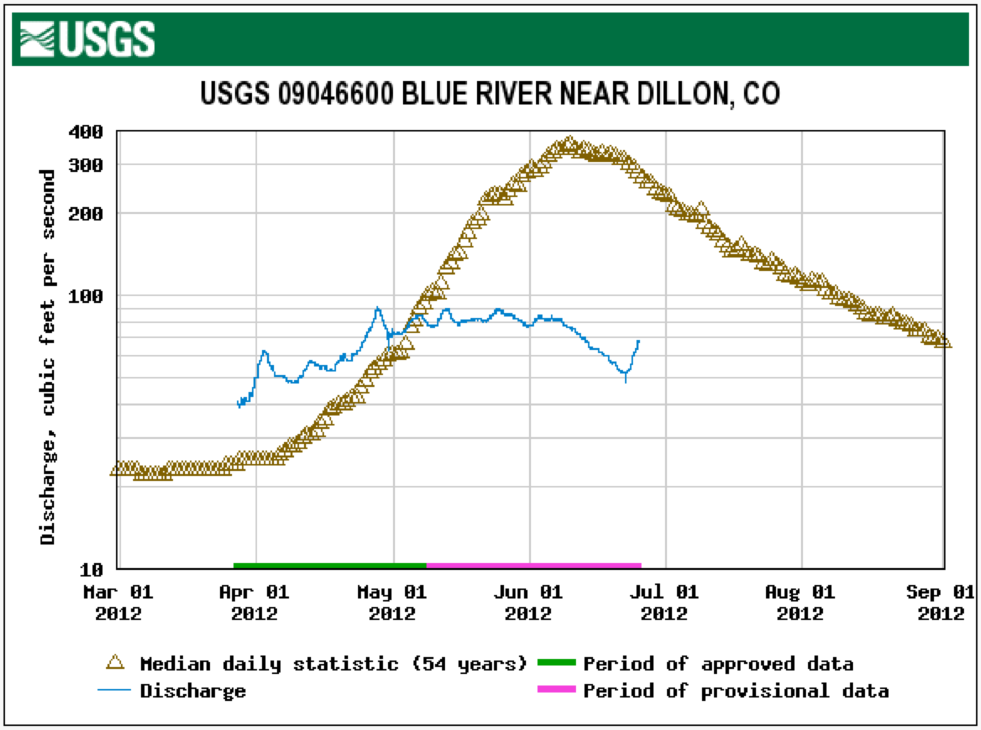
During WY 2012, three fall and early winter dust storms were observed low in the snowpack at Senator Beck Basin, and one of these layers (likely D3) was discernible at Hoosier Pass in our CODOS snow profiles. And, although dust-on-snow events D9-D12 fell well after the date of SAG at our Hoosier Pass CODOS site in WY 2012, those later events further reduced snow albedo and enhanced snowmelt rates in the remaining snowpack at higher elevations and on shady subalpine aspects in the nearby terrain.



WY 2012 SWE accumulation and ablation at Hoosier Pass Snotel with upper and lower quartiles of period of record shown in light grey, middle quartiles in dark grey surrounding median trace for period of record, and mean trace for 1971-2000 period.

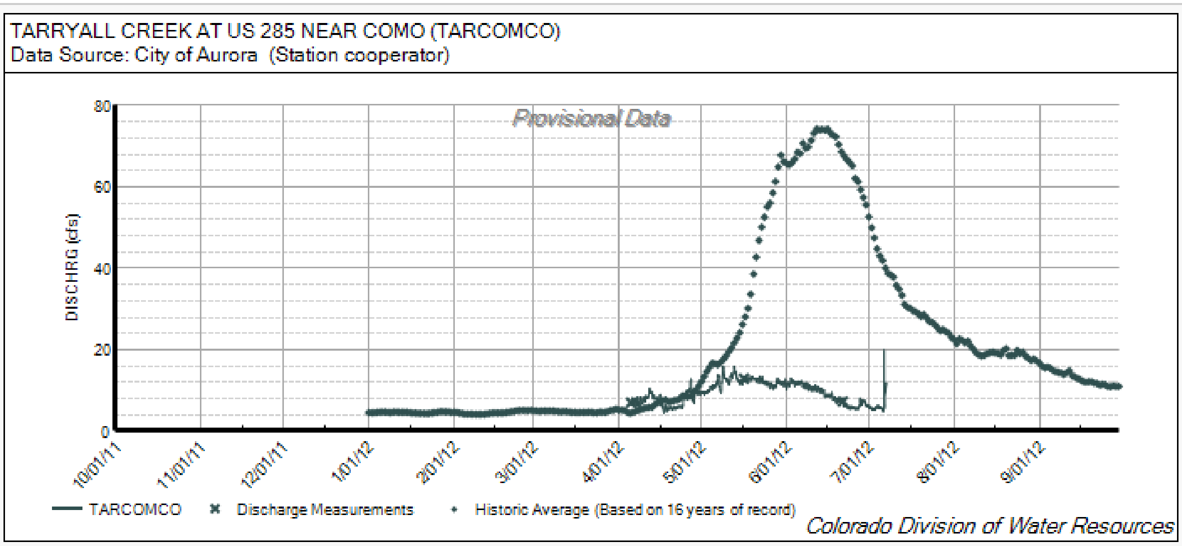
Because of the early date of WY 2012 peak SWE at Hoosier Pass Snotel, on March 28th, spring 2012 produced a two-step descending limb in the SWE plot rather than the single, steep plunge following the very delayed peak SWE in 2011. In 2012, snowpack ablation at Hoosier Pass Snotel gradually accelerated in early April until storms in mid-April produced a small rebound in SWE. Then, in late April, under the influence of unseasonably warm temperatures and modest reductions in snow albedo from dust, melt rates accelerated again, to a higher rate. Overall, the Hoosier Pass Snotel site required 48 days to ablate 13.1" of SWE (including 2.9" of precipitation after peak SWE), averaging just 0.27" of SWE loss per day.

STREAM FLOWS



WY 2012 USGS Blue River near Dillon, CO stream gauge data for a 121 sq. mi. drainage area in the upper Blue River watershed, above 9,020'. Current year and historic data reflect transmountain diversions upstream by Boreas Pass ditch and Hoosier Pass tunnel.

Given the very dry spring and below-average snowpacks throughout the Front Range mountains, below average snowmelt runoff in those watersheds was unsurprising. Streamflow data reflecting snowmelt runoff behavior in the Hoosier Pass vicinity are limited. However, even with 0-2 cfs diversions at the Monte Cristo site and 1-4 cfs at the Bemrose-Hoosier site and unknown diversions to the Boreas Ditch throughout the spring, the Blue River near Dillon hydrograph shows evidence of an early start to runoff with substantially above-average flows in April and a peak in late April. May flows surged and matched the April peak, but then began declining. By mid-June flows had fallen below those expected two months later, in September. Tarryall Creek at Como data also suggest an early runoff peaking in mid-May rather than the normal mid-June date. More importantly, those data document extremely low flows throughout the snowmelt season, dropping below late-September levels in June.



WY 2012 Tarryall Creek at US 285 near Como Stream Gauge data for a 24 sq. mi. drainage area, above 9,935'.

In addition to the very warm temperatures associated with prolonged periods of dry and sunny weather in late winter and spring 2012, even the comparatively weak dust-on-snow events D4 (March 6th) and D8 (April 6th) played a role in this early Hoosier Pass locale runoff, incrementally reducing albedo and hastening the ripening of the snowpack in late March, to isothermal, and then absorbing and adding additional solar energy to the snowmelt energy budget during subsequent periods of exposure at the snowpack surface. Additional dust events in late May further reduced snow albedo in the remaining snowpack, hastening the extreme drying of Front Range mountain systems.

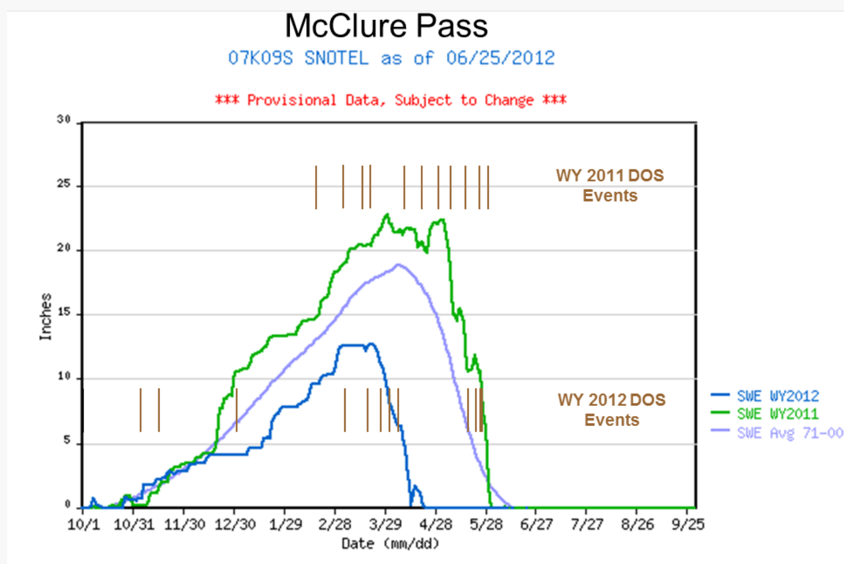
WATER YEAR 2012 CODOS SUMMARY FOR MCCLURE PASS

Summary | Snowpack | Melt Rate | Stream Flows

SUMMARY

Water Years 2011 and 2012 are a case study in interannual variability of Colorado snowpack formation and ablation driven by vastly different late winter and spring weather conditions, perhaps representing seasonal extremes. In dramatic contrast with the unrelenting storms of Mar/Apr/May 2011, extremely dry late-winter and spring weather in 2012 resulted in low values of peak SWE, very early in the spring.

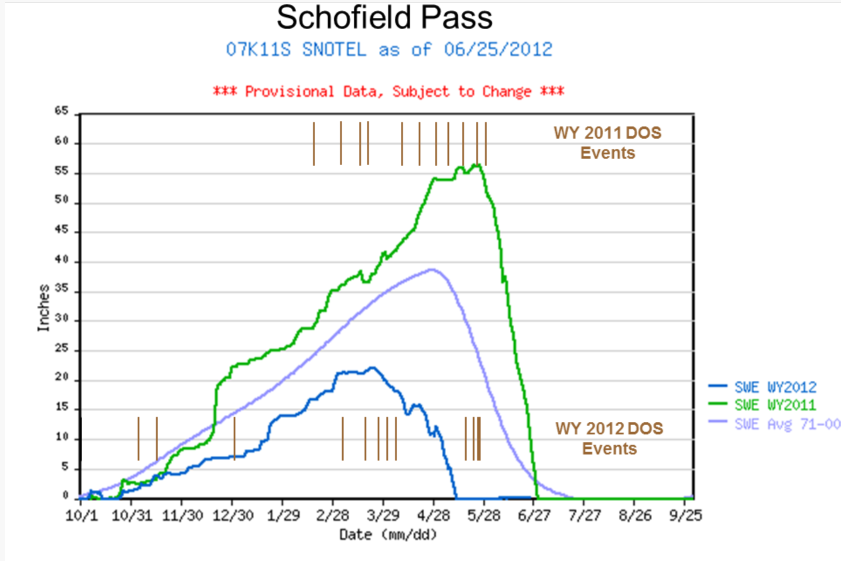
On the other hand, the past two seasons produced comparatively smaller differences in dust-on-snow conditions, with WY 2012 coming close to matching WY 2011 at the Senator Beck Basin Study Area, our baseline monitoring site. Locally, WY 2012 desert dust concentrations in the McClure Pass locale were generally as intense as those observed at Senator Beck Basin and, given the very dry winter, the McClure Pass CODOS site snowpack was among the first of our CODOS sites to reach "snow all gone" (SAG). Streamflow data from the nearby Muddy Creek stream gauge, and other nearby gauges, document a substantial advance in the entire snowmelt runoff cycle, and reduced total runoff.



SNOWPACK & DUST DISCUSSION

Water Year 2012 snowpack formation at the McClure Pass Snotel site began with near-average snow accumulations until mid-December. Then, SWE values fell into the lower quartile of values in the McClure period of record, until peak SWE in late March (see Snotel projection plot below). Nearby, at the Schofield Pass Snotel, SWE values almost immediately fell into the lower quartile of values in that site's period of record and also remained there until 2012 peak SWE, also in late March (see Snotel projection plot).

Our March 16th snowpit at the McClure Pass CODOS site, ~150 feet from the Snotel, found only 73 cm (29") of snow, already isothermal and wet throughout, with dust layer D4 at the snowpack surface. That snowpit, on a 6° slope facing south-southwest, contained 256 mm (10.1") of SWE, versus 12.6" of SWE then reported by the



SWE accumulation and ablation at McClure Pass and nearby Schofield Pass for Water Years 2011 and 2012, with dust-on-snow events shown, by date, as brown bars for both water years (as observed at the Senator Beck Basin Study Area).

McClure Pass Snotel. Soon thereafter, both McClure and Schofield Passes received the first significant storm since March 2nd, delivering peak SWE to both. WY 2012 peak SWE at McClure Pass was only 12.7”, short of the 1971-2000 average of 18.9” and far short of the 22.8” peak of 2011. At Schofield Pass, WY 2012 peak SWE occurred on March 24th, at 21.9”, also far short of that site’s 1971-2000 average of 38.5” and very far short of the 56.3” of peak SWE in WY 2011.

Immediately following peak SWE, both the McClure Pass and Schofield Pass Snotel sites began losing snowpack and SWE values soon fell below all April measurements in the period of record. The McClure Pass Snotel lost all snowpack (SAG) at the earliest date in its history, on April 23rd. Schofield Pass still had snowpack going into May, albeit at the lowest SWE levels in its period of record, and eventually reached SAG on May 11th, also the earliest date in that site’s history.

Looking south at the McClure Pass Snotel station, in the background, from the recently snow-free CODOS snowpit site on April 11th, **2012**, and from the same location on May 18, **2011**. At just 9,500’, the McClure Pass site is among our lowest elevation CODOS plots and typically among the first to reach SAG each spring.

During WY 2011 eleven dust events occurred at Senator Beck Basin containing a total of 14 grams of dust per square meter. Most or all of those events were found in our spring 2011 CODOS snow profiles at McClure Pass, although the final event fell just a few days before McClure Pass Snotel SAG on June 1.

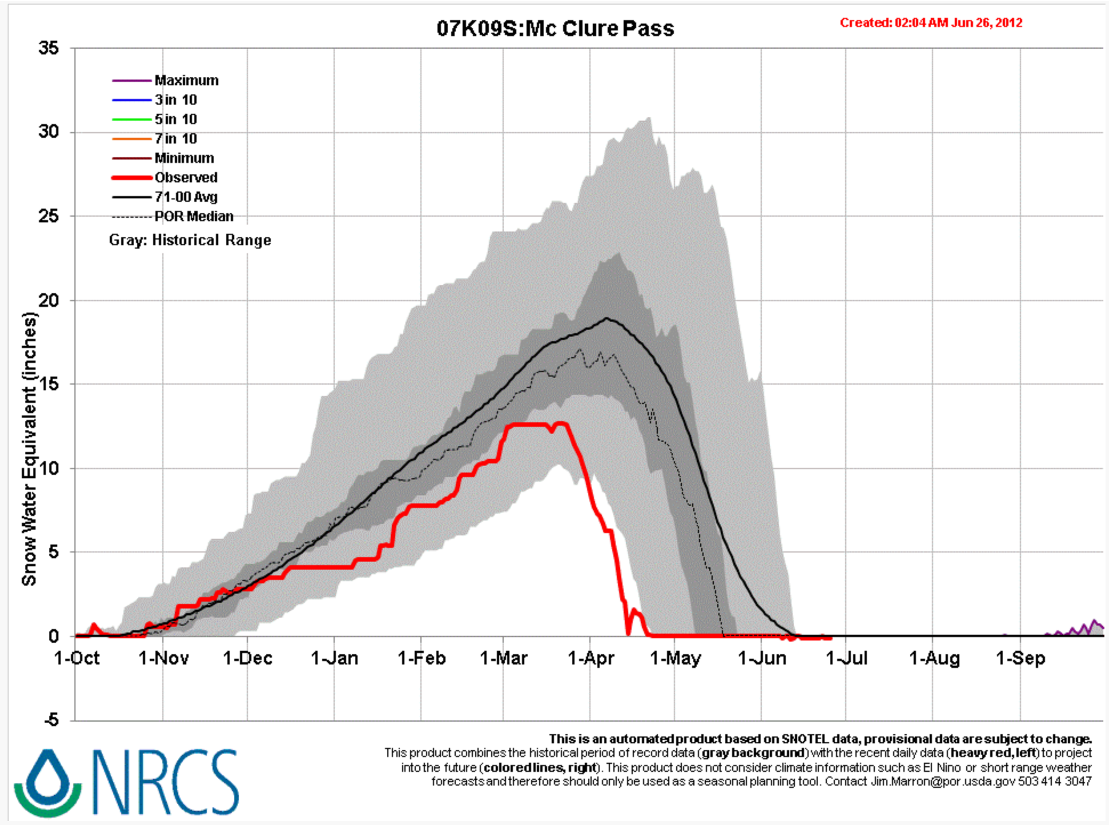
During WY 2012 a similar twelve dust events occurred at Senator Beck Basin containing a total of ~10-12 grams of dust per square meter (see Senator Beck Basin Summary – Dust Log discussion). But, in a dramatic switch, late winter and spring 2012 were exceptionally dry, with widely spaced and comparatively small winter storms (see Senator Beck Basin – Winter Storm Log Discussion). Although SAG may have occurred at the McClure Pass CODOS site before WY 2012 dust layer D8 fell, on April 6th, dust layers corresponding with dust events D1, D3 and D4 were present in the snowpack at that site, in our March 16th snow profile, and reductions in snow albedo at McClure Pass were very similar to those observed in the Senator Beck Basin Study Area a few days earlier. The final four dust events, in late May, likely did fall onto remaining alpine snowpack at the higher elevations surrounding McClure and Schofield Passes, further reducing snow albedo for the remainder of the snowpack season.

McClure Pass Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Period Add Precip	Period Mean Temp C	Adjusted Daily Mean Loss SWE	Maximum 5-Day Moving Average of Daily Loss of SWE
WY 2006	4/8/2006	20.5	30	1.5	6.6	0.73	1.14
WY 2007	3/13/2007	15.5	56	5.9	4.7	0.38	1.38
WY 2008	4/16/2008	29.3	40	2.3	5.5	0.79	1.74
WY 2009	4/8/2009	24.2	30	2.4	5.5	0.89	1.68
WY 2010	4/10/2010	20.3	38	3.0	5.0	0.61	1.10
WY 2011	3/31/3011	22.8	62	9.0	4.5	0.51	1.78
WY 2012	3/22/2012	12.7	32	1.7	6.1	0.45	1.06
Max	04/16/08	29.3	62	9.0	6.6	0.9	1.8
Min	03/13/07	12.7	30	1.5	4.5	0.4	1.1
Range		16.6	32	7.5	2.0	0.5	0.7
Median		20.5	38	2.4	5.5	0.6	1.4

Analysis of McClure Pass Snotel data for 2006-2012 snowmelt seasons showing date and quantity of peak SWE, days from peak SWE to "snow all gone" (SAG), total additional precipitation after date of peak SWE, an "adjusted" mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG.

This discussion references CODOS Snotel site data and analyzes rates of snowmelt from Spring 2006 to the present, spanning the period during which we've rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. As discussed in prior CODOS Updates, many Snotel sites exhibit a radiative regime where surrounding trees reduce the access of incoming solar radiation to snowpack over the SWE measuring snow pillow, and where re-radiation of long wave energy from that vegetation and reduced skyview may inhibit radiant cooling and extend surface snowmelt during nighttime hours. As a consequence, Snotel sites often do not experience the maximum effects of dust-on-snow on snowmelt timing and rates, as compared to generally level, open meadow sites where solar access is unimpeded and snowmelt energy budgets and snowpack ablation are measured. The McClure Pass Snotel site does experience partial shading, by primarily aspen tree trunks (as seen in the photo above). Snowmelt rates at the McClure Pass Snotel do lag those at the slightly south-sloping CODOS snowpit plot just to the north, in an open meadow, but not to the extent observed at more densely forested Snotel sites. The Schofield Pass Snotel site also experiences less reduction in solar access than many Snotel sites.

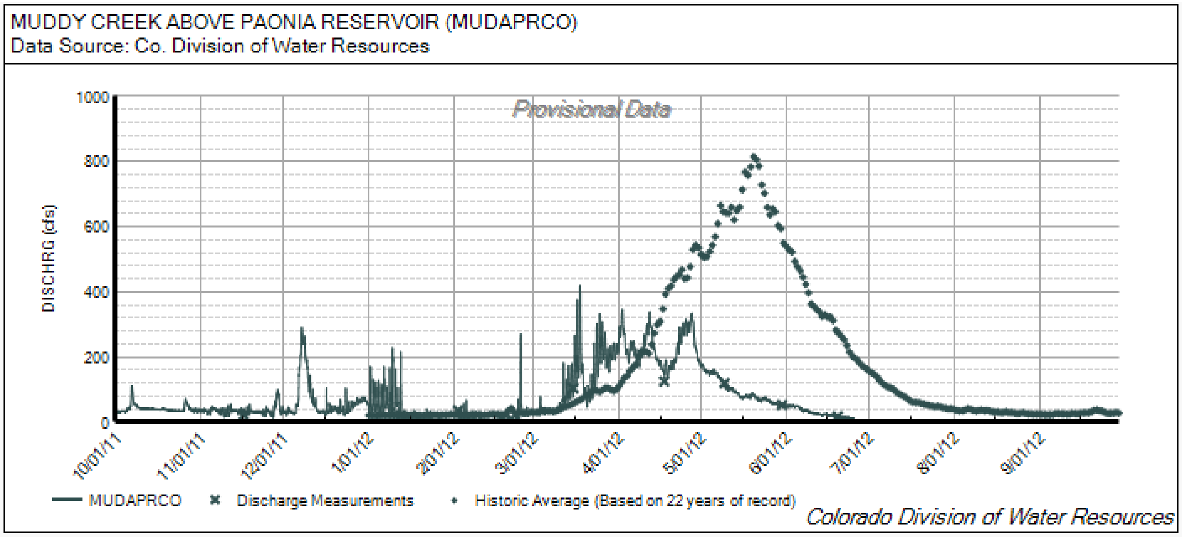


WY 2012 SWE accumulation and ablation at McClure Pass Snotel, with upper and lower quartiles of period of record shown in light grey, middle quartiles in dark grey surrounding median trace for period of record, and mean trace for 1971-2000 period.

Despite the comparatively early date of WY 2012 peak SWE at McClure Pass Snotel, on April 23rd, spring 2012 produced a steep descending limb in the SWE plot similar to the single, very steep plunge following the second peak SWE in 2011, albeit with a slight 'bounce' in SWE just before SAG (see figures above). In a departure from our other CODOS sites, Spring 2012 actually *did not* produce the earliest date of Peak SWE at McClure Pass in the past seven years. That distinction fell to WY 2007, which also produced the lowest rate of daily SWE loss. However, WY 2012 did record the lowest value of peak SWE and, despite showing the second slowest rate of melt, 2012 also produced the earliest date of SAG in the entire Snotel period of record at McClure Pass.

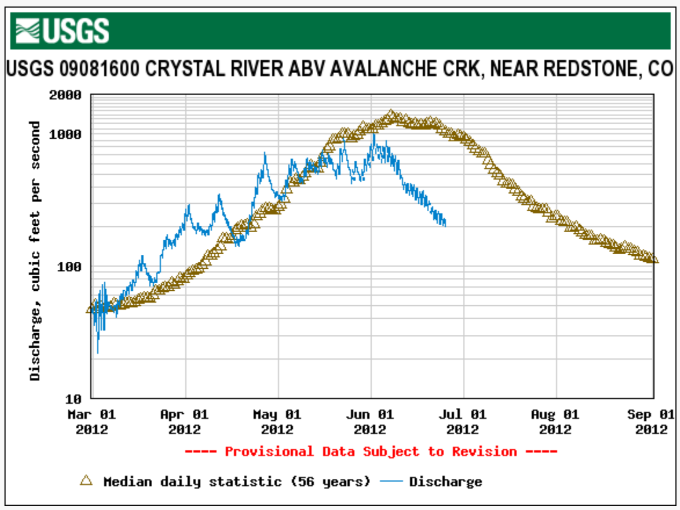
About 16 miles to the southeast, at 10,700', and at the headwaters of both the Crystal and East rivers, WY 2012 snowpack ablation at the Schofield Pass Snotel more closely resembled the two-phased process observed at most other CODOS Snotel sites, with a steady but moderate melt rate immediately following peak SWE, an acceleration in early April subsequently interrupted by small rebounds in SWE during stormy weather in mid and late April, followed by a final plunge to SAG. Largely because of the very early start of peak SWE and subsequent snowmelt in WY 2012, compared to the extremely late peak SWE and start of snowmelt in WY 2011, these two back-to-back seasons produced the lowest (0.53" per day in 2012) and highest (1.64" per day in 2011) rates of dust-enhanced daily average SWE loss observed at Schofield Pass, and the highest 5-day moving average rate of melt (at 2.44") of all our CODOS sites, for all years.

STREAM FLOWS



WY 2012 Muddy Creek above Paonia Reservoir stream gauge data for a 246 sq. mi. drainage area; no elevation is given.

Given the very dry spring and sub-par snowpacks throughout the western Elk mountains, below average snowmelt runoff in Muddy Creek and the Crystal River was unsurprising. The Muddy Creek above Paonia Reservoir hydrograph shows an early start to runoff with substantially above-average flows in March and early April to a well-below-average peak, followed by an initially rapid but gradually decelerating decline in flows. As was typical throughout the state, by the end of June streamflows had fallen below levels expected two months later, in September.



WY 2012 USGS Crystal River above Avalanche Creek stream gauge data for a 167 sq. mi. drainage area in the upper Crystal River valley, above 6,905'. Current year and historic data reflect a few small diversions for irrigation upstream of the gauge.

The Crystal River hydrograph above presents a very similar pattern, with an early start to runoff at substantially above-average flows in March and early April. Flows peaked at half of average discharge but, unlike most sites, near average timing. And, as has been the norm elsewhere, June flows fell to levels expected in late summer.

In addition to the very warm temperatures associated with prolonged periods of dry and sunny weather in late winter and spring 2012, dust-on-snow events D4 (March 6th) and D8 (April 6th) played a role in the early and high runoff levels on the ascending limbs of these hydrographs, reducing snow albedo and hastening the ripening of the snowpack in late March, to isothermal. That and additional dust then continued absorbing and adding solar energy to the snowmelt energy budget during subsequent periods of exposure at the snowpack surface in April and May. Additional dust events in late May, particularly D12 on May 26th, further reduced snow albedo in the scant remaining high elevation snowpack in the western Elk Mountains and hastened the final days of snowmelt runoff.

CODOS Water Year 2012 Updates > 2012 Summary > Park Cone

WATER YEAR 2012 CODOS SUMMARY FOR PARK CONE

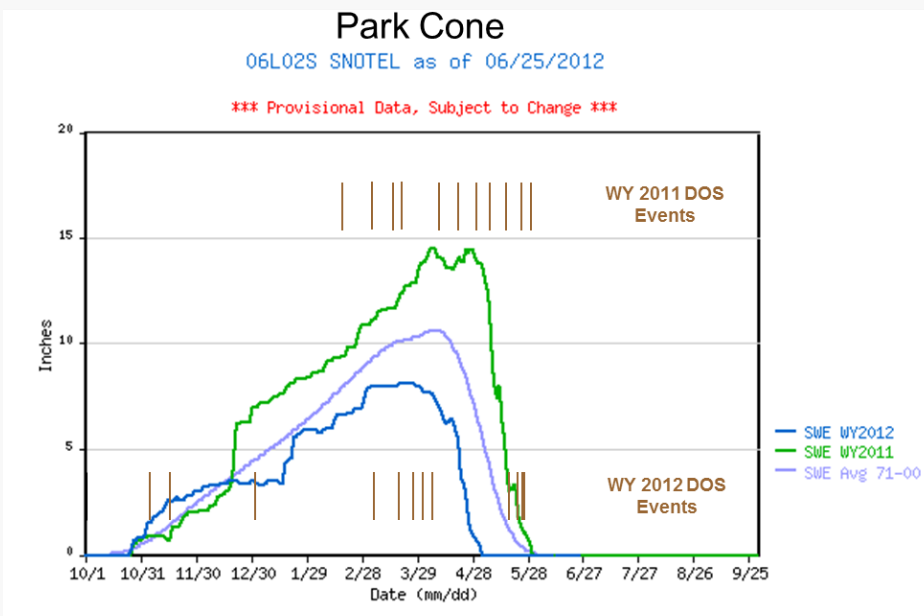
Summary | Snowpack & Dust | Melt Rates | Stream Flows

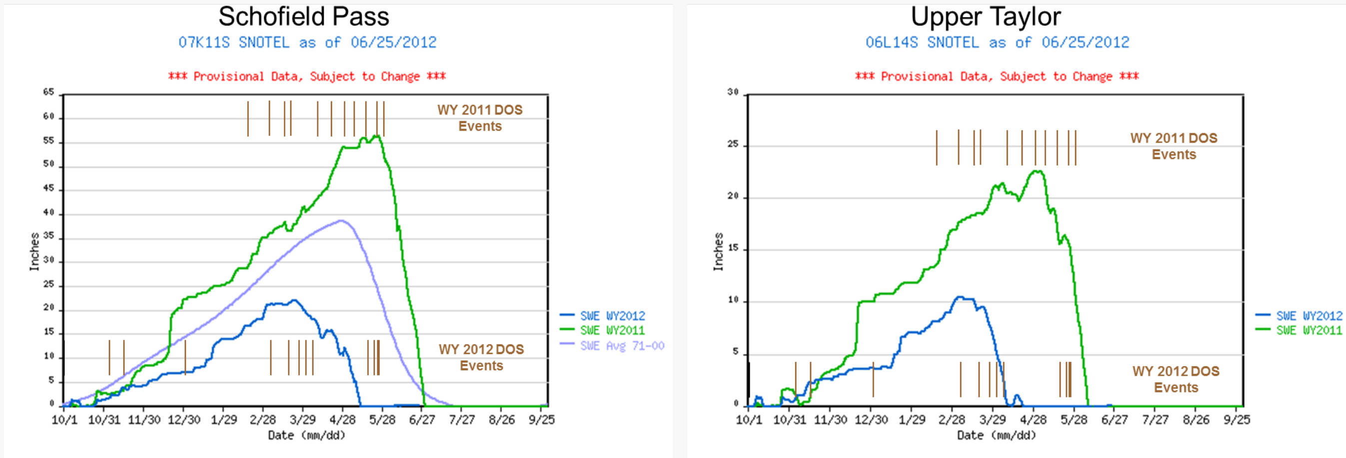
SUMMARY

Water Years 2011 and 2012 are a case study in interannual variability of Colorado snowpack formation and ablation driven by vastly different late winter and spring weather conditions, perhaps representing seasonal extremes. In dramatic contrast with the endless storms and tremendous snowpacks of Mar/Apr/May 2011, extremely dry late-winter and spring weather in 2012 resulted in very low values of peak SWE, very early in the spring, in the northern headwaters of the Gunnison Basin, and minimal valley floor snowpack.

On the other hand, overall, the past two seasons produced comparatively similar dust-on-snow conditions in the Colorado mountains, although the Taylor Park locale in particular experienced less dust and albedo reduction than other sites monitored by CODOS. Spring 2012 dust effects on snowpack ablation at Park Cone and elsewhere in the Taylor River watershed occurred in two phases, at different rates. Beginning in March, comparatively weak dust-on-snow layers remained exposed at the snowpack surface for prolonged periods, absorbing enough additional solar energy to advance snowpack warming, enabling snowmelt runoff to begin. During April, despite occasional snowfalls, dust events D4-D8 incrementally reduced snow albedo and snowpack ablation accelerated, aided by unseasonably warm weather. Snowmelt runoff began accelerating well in advance of long-term average timing, then slowed during the unsettled weather in April, then peaked low and early in mid May as the final four dust events of the season fell on the remaining high elevation snowpack.

SNOWPACK & DUST DISCUSSION





SWE accumulation and ablation for Water Years 2011 and 2012, with dust-on-snow events shown, by date, as brown bars for both water years (as observed at the Senator Beck Basin Study Area). Park Cone and Schofield Pass plots show 1971-2000 mean SWE accumulation data, whereas the period of record at Upper Taylor is just three winters, to-date, and no mean has been calculated.

In a reversal of early winter WY 2011, Water Year 2012 snowpack formation at Park Cone Snotel began well but stalled in December. After a strong rebound in January, Park Cone hovered just below average until stalling again in early March. Due to the very dry late-winter and spring experienced throughout Colorado, WY 2012 peak SWE at Park Cone was only 8.1”, short of the 1971-2000 average of 10.6” and far short of the 14.4” peak of 2011. Peak SWE 2012 also occurred early in the season, on March 27th, eleven days earlier than the 1971-2000 average of April 7th and a full month earlier than the latter of two nearly equal equivalent Peak SWE values in 2011, on April 28th, 2011.

Further up the watershed, the Upper Taylor Snotel recorded a larger but earlier WY 2012 peak SWE of 10.4” on March 7th. To the west, the Schofield Pass Snotel peaked at 21.9” on March 24th, less than half of and two months earlier than peak SWE in 2011 (see Schofield Pass Snotel projection plot). Although WY 2012 peak SWE at Park Cone fell within the lower quartile of data for the period of record (see Park Cone Snotel projection plot below), peak SWE at Schofield Pass occurred at the bottom of the lower quartile of values, and thereafter fell well below all prior period of record daily SWE values for the duration of the season. Of all three of these Snotel sites, Park Cone exhibited less overall variation between WY 2011 and 2012 than Upper Taylor and Schofield Pass, but was still well below par. At lower elevations, we were particularly struck by the absence of snowpack in the Gunnison valley floor during our CODOS field campaigns.

At the CSAS Senator Beck Basin Study Area at Red Mountain Pass the total number of events and approximate total mass of dust deposited during WYs 2011 and 2012 were similar, at 11 and 12 events, and 14 and ~10-12 grams per square meter, respectively (see Senator Beck Basin Summary – Dust Log discussion). However, perhaps because of the same local terrain influences on weather that result in Park Cone being a comparatively dry site, both seasons saw less dust deposited at Park Cone than at Senator Beck Basin, and Park Cone was clearly the least dusty of all our CODOS dust monitoring sites in WY 2012. Nonetheless, dust did play a role in snowpack ablation during both seasons, albeit in very different scenarios.

During WY 2011 eleven dust events occurred at Senator Beck Basin, many of which were confirmed at Park Cone in CODOS snow profiles. However, relentless accumulation of late winter and spring snow routinely buried new dust layers and restored high snow albedo values throughout the State, throughout April and May. That sustained winter-like weather also conserved, for a time, the snowpack cold content measured in our March 29th, 2011 snowpit at Park Cone. Then, sometime prior to our April 22nd, 2011 snowpit, the Park Cone snowpack became isothermal. Within a week, rapid snowmelt began in tandem with several additional dust-on-snow events. Although the Park Cone Snotel was very near “snow all gone” (SAG) during the final and largest dust storm of WY 2011, that D11 event of May 29th did fall onto still-extensive higher elevation snowpacks in the Taylor River watershed, further reducing albedo and enhancing snowmelt rates for the remainder of the very large runoff.

In sharp contrast, late winter and spring 2012 were exceptionally dry, with widely spaced and comparatively small winter storms (see Senator Beck Basin – Winter Storm Log Discussion). WY 2012 dust loading and reductions in snow albedo at Park Cone and in lower Taylor Park were weaker than at the Senator Beck Basin Study Area. Further, because the Park Cone CODOS snow pit site slopes 11° to the north, the angle of incidence of sunlight hitting the snowpack surface is lower. Radiative forcing by dust is less intense at Park Cone, given the same dust loading, than at our Senator Beck Basin study plots, which both slope just 3° to the northeast.

During our March 14th snow profile at Park Cone, we found a weak layer of event D4 dust at the snowpack surface, slightly reducing snow albedo. Nonetheless, several inches of melt/freeze, polycrystal grains in the near-surface snow, including actively melting forms, indicated that the reduction in snow albedo was still sufficient to result in surface melt despite an air temperature of -2° C at the time. Even with surface melt in progress, just 10 cm (4”) below the surface the snow temperature was -7° C, and -7.5° C another 10 cm below that, with a mean snowpack temperature of -3.5° C.

Despite the minimal reduction in snow albedo caused by dust layer D4, dust was hastening snowpack warming to 0° C and by our next site visit, on April 9th, the snowpack had long-since become isothermal at 0° C throughout and consisted entirely of polycrystal (melt) forms. Once isothermal, all additional energy absorbed by dust layers D4-D8 (as present) at the Park Cone snowpack surface resulted in enhanced rates of snowmelt and snowpack ablation. Snow all gone (SAG) followed very quickly in our snowpit plot, prior to dust events D9-12, but was more delayed by tree shading at the adjoining Park Cone Snotel site (see Melt Rate discussion below). Those late-season dust events, including D12 on May 26th, did fall onto the remaining high-elevation snowpack in the upper Gunnison watershed, including the Lake Fork locale.

Upper Gunnison River Water Conservancy District general manager Frank Kugel at the Park Cone CODOS snowpit site on April 9th, 2012. This snowpit was isothermal and rapidly approaching "snow all gone" (SAG), with free water throughout the snowpack and with merged dust layers corresponding to WY 2012 events D4-D8 at the surface producing minor reductions in snow albedo.

Spring 2012 air temperatures did not vary substantially from prior snowmelt seasons. Despite the minimal snowpack, and the sustained periods of dry, sunny weather supporting the dust-enhanced radiative forcing of snowmelt, the Park Cone Snotel did not record its earliest date of SAG in its period of record, as many CODOS site Snotels and the nearby Schofield Pass Snotel did. Rather, the entire snowmelt cycle remained within the lower quartile of the Park Cone Snotel period of record, to SAG on May 3rd, 2012. Snowmelt at the Slumgullion Pass Snotel also fell within the historically early lower quartile of SAG dates.

MELT RATES

Park Cone Snotel Snowmelt Season Summary Data
Prepared by CODOS - CSAS

	Date Peak SWE	Peak SWE	Days to SAG	Period Add Precip	Period Mean Temp C	Adjusted Daily Mean Loss SWE	Maximum 5-Day Moving Average of Daily Loss of SWE	SBBSA DOS Post Peak SWE
WY 2006	4/7/2006	11.3	31	0.9	3.7	0.39	0.58	4
WY 2007	4/18/2007	7.8	17	0.5	4.5	0.49	0.60	3
WY 2008	4/14/2008	17.7	47	2.8	3.8	0.44	1.00	4
WY 2009	4/6/2009	13.2	38	1.4	3.5	0.38	0.84	4
WY 2010	4/10/2010	10.8	41	2.4	3.1	0.32	0.62	5
WY 2011	4/28/2011	14.4	33	1.4	4.0	0.48	1.00	5
WY 2012	3/27/2012	8.1	37	0.3	3.9	0.23	0.62	6
Max	04/28/11	17.7	47	2.8	4.5	0.5	1.0	6
Min	03/27/12	7.8	17	0.3	3.1	0.2	0.6	3
Range	32	9.9	30	2.5	1.4	0.3	0.4	3

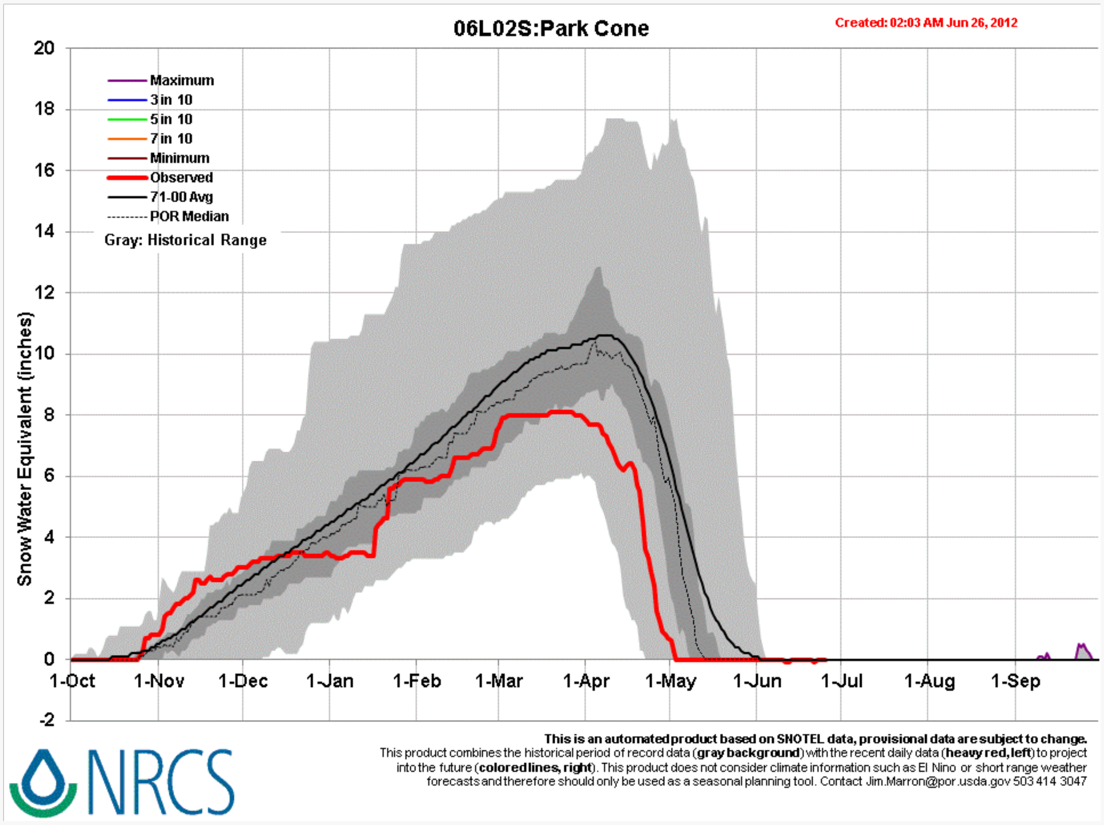
Analysis of Park Cone Snotel data for 2006-2012 snowmelt seasons showing date and quantity of peak SWE, days from peak SWE to "snow all gone" (SAG), total additional precipitation after date of peak SWE, an "adjusted" mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG.

This discussion references CODOS Snotel site data and analyzes rates of snowmelt from Spring 2006 to the present, spanning the period during which we've rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. As discussed in prior CODOS Updates, many Snotel sites, including Park Cone, exhibit a radiative regime where surrounding trees reduce the access of incoming solar radiation to snowpack over the SWE measuring snow pillow, and where re-radiation of long wave energy from that vegetation and reduced skyview may sustain periods of surface snowmelt during nighttime hours. As a consequence, Snotel sites often do not experience the maximum effects of dust-on-snow on snowmelt timing and rates, as compared to generally level, open meadow sites where solar access is unimpeded and snowmelt energy budgets and snowpack ablation are measured. Nonetheless, the Snotel network is the only spatially extensive system monitoring snowmelt throughout the Colorado mountains and year-to-year comparisons of

Snotel melt rate data may yield insights into dust effects on local watershed-scale processes.

The Park Cone Snotel site on March 29, 2011, with 54” of snow containing 13.4” of SWE, and still gaining SWE. This photo, looking east, shows the adjoining forest cover shading the site from the east, south, and west, blocking direct solar access to the snow surface over the snow pillow and reducing the influence of dust on snowmelt rates at this Snotel site.

During WY 2012, three fall and early winter dust storms were observed low in the snowpack at Senator Beck Basin, but none of these layers was discernible in the Park Cone snowpack. And, although several dust-on-snow events fell after the date of SAG Park Cone in WY 2012, those later events did nonetheless further reduce snow albedo and enhance snowmelt rates in the remaining snowpack at higher elevations and on shady subalpine aspects in the nearby terrain in the Gunnison River basin.

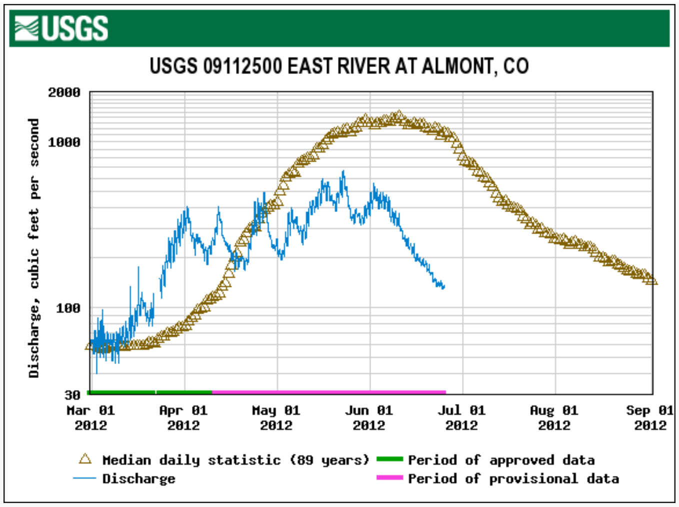


WY 2012 SWE accumulation and ablation at Park Cone Snotel, with upper and lower quartiles of period of record shown in light grey, middle quartiles in dark grey surrounding median trace for period of record, and mean trace for 1971-2000 period.

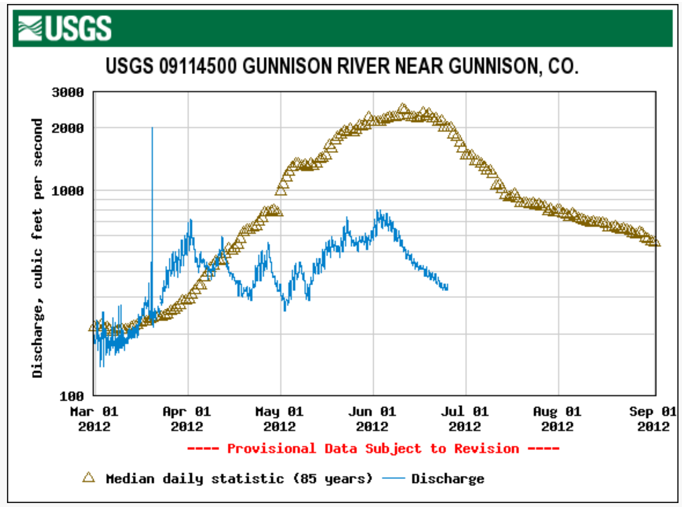
Because of the comparatively early date of WY 2012 peak SWE at Park Cone Snotel, on March 27th, and the comparatively weak dust loading and albedo reductions there last season, spring 2012 produced a much different descending limb in the SWE plot than the single, very steep plunge following the second peak SWE in 2011. In 2012, snowpack ablation gradually accelerated in late March and early April until a small rebound from new snow in mid-month. Melt rates then sharply accelerated as dust event D8 emerged and merged with underlying dust. Overall, as seen in the table above, Spring 2012 produced the lowest value and earliest date of Peak SWE in the past seven years. Further, this prolonged snowmelt period required more days (37) to fully ablate the snowpack than were required to melt the much larger snowpack the year before (33 days). Since 2006, WY 2012 experienced the lowest rate of daily SWE loss (0.23” per day) for the full snowmelt period whereas 2011 melt rates were among the highest at Park Cone. The entire WY 2012 snowmelt cycle remained within the historic range of snowmelt timing in the Park Cone period of record. On the southern edge of the Gunnison Basin, the Slumgullion Pass Snotel (also heavily shaded by adjoining forest) also experienced the full snowmelt cycle within the lower quartile of the period of record.

This was not the case at the Schofield Pass Snotel, where peak SWE on March 24th, 2012 matched the lowest value of SWE in the entire period of record for that day (see Schofield melt rate table). Schofield remained outside the historic range of SWE values for the remainder of the snowmelt cycle to SAG on May 10th. The Schofield Pass Snotel site is less shaded than most Snotel sites, affording better solar access to the snowpack over the snow pillow. Dust effects on snowmelt rates at this Snotel more closely resemble those in a level, open meadow.

STREAM FLOWS



WY 2012 USGS East River at Almont Stream Gauge data for a 289 sq. mi. drainage area in the upper East River watershed, above 8,006'. Current year and historic data reflect diversions for 7,400 of irrigation upstream.

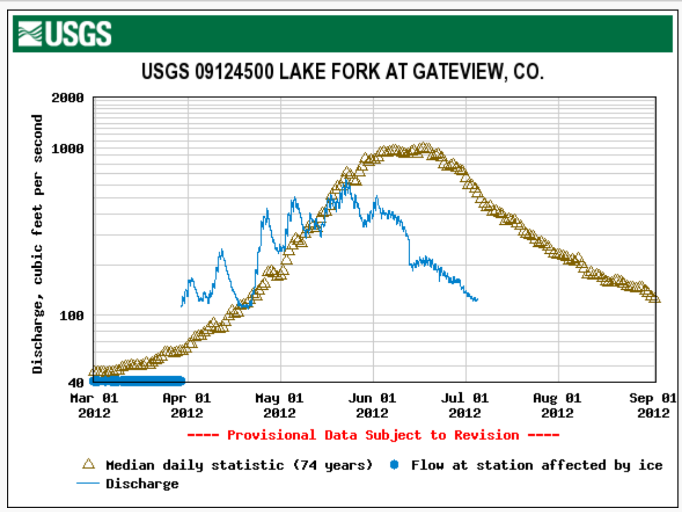


WY 2012 USGS Gunnison River near Gunnison Stream Gauge data for a 1,012 sq. mi. drainage area in the upper Gunnison River watershed, above 7,655'. Current year and historic data reflect regulated flows from Taylor Park Reservoir and diversions for ~22,000 of irrigation upstream of the gauge.

Streamflow data from the USGS East River at Almont and Gunnison River near Gunnison gauges reflect an early and severely reduced snowmelt runoff in WY 2012. Enhanced by unseasonably warm and dry weather and comparatively minor but nonetheless effective reductions in snow albedo from dust in March and throughout April, streamflows surged to several times average discharge levels for late March until intersecting with median levels in mid-April and then falling and remaining well below median rates for the duration. Both gauges recorded peak flows well in advance of normal peak date and more than 50% below normal discharge values. Steep declines in discharge then followed in early June and fell to levels normally seen by September 1st.

Overall, these East River and Gunnison River hydrographs present large advances in the timing of WY 2012 runoff at both locations, with the center of their substantially reduced runoff mass occurring several weeks earlier than normal. In addition to the very warm temperatures associated with prolonged periods of dry and sunny weather, dust-on-snow was also factor in these runoff patterns, hastening the "ripening" of the snowpack in March, to isothermal, and then absorbing and adding additional solar energy to the snowmelt energy budget in April and the remainder of the unusually dry spring season.

Farther south, due to the somewhat better snowpack in the northern San Juan Mountains, median or better flows were sustained in the Lake Fork of the Gunnison until peak flow in late May. Dust concentrations in this locale were stronger than those observed in Taylor Park. Eventually, here too, June flows fell rapidly to levels normally expected two months later, at the end of August.

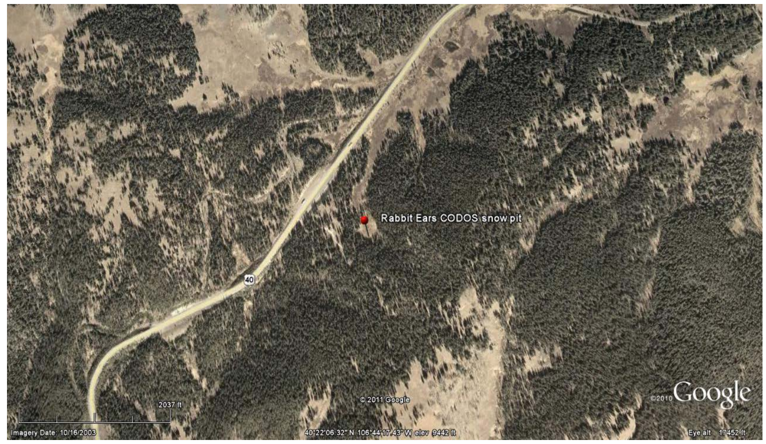


WY 2012 USGS Lake Fork at Gateway stream gauge data for a 334 sq. mi. drainage area in the Lake Fork of the Gunnison watershed, above 7,828'. Current year and historic data reflect diversions for 1,600 of irrigation upstream of the gauge.

CENTER FOR SNOW & AVALANCHE STUDIES

WATER YEAR 2012 CODOS SUMMARY FOR RABBIT EARS PASS

Summary | Snowpack | Melt Rate | Stream Flows



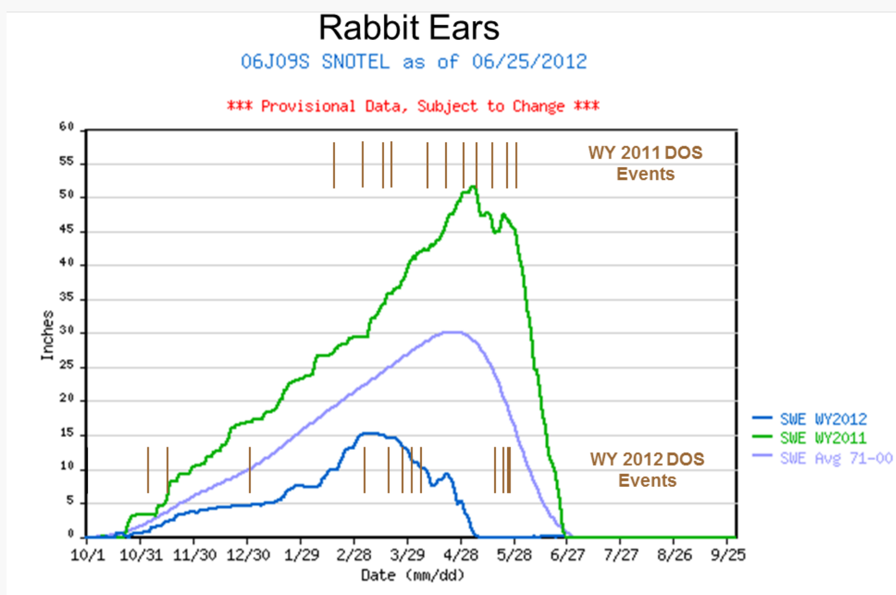
SUMMARY

Water Years 2011 and 2012 are a case study in interannual variability of Colorado snowpack formation and ablation driven by vastly different late winter and spring weather conditions, perhaps representing seasonal extremes. In dramatic contrast with the unrelenting storms of Mar/Apr/May 2011, extremely dry late-winter and spring weather in 2012 resulted in low values of peak SWE, very early in the spring.

On the other hand, the past two seasons produced comparatively smaller differences in dust-on-snow conditions, with WY 2012 coming close to matching WY 2011 at the Senator Beck Basin Study Area, our baseline monitoring site. Locally, WY 2012 desert dust concentrations in the Rabbit Ears Pass locale were only somewhat less intense than those observed at Senator Beck Basin and spring 2012 snowpack “ripening” was enhanced by those reductions in snow albedo. The Rabbit Ears Pass CODOS site snowpack became isothermal sometime prior to April 10th, with several dust layers merged at the snowpack surface. Streamflow data from the nearby USGS Yampa River at Steamboat Springs gauge document a substantial advance in the entire snowmelt runoff cycle, and reduced total runoff.

SNOWPACK & DUST DISCUSSION

From the very start, Water Year 2012 snowpack formation at the Rabbit Ears Pass Snotel fell behind average and by December SWE accumulations had fallen into the lower quartile of values for the period of record (see Snotel projection plot below). New record-low values of SWE began in January, briefly rebounded back into the lower quartile in mid-February, then reached peak SWE very early, on March 13th, at just 15.2”, well short of the 1971-2000 average of 30.2” and six weeks earlier than the April 24th average date of peak SWE. Peak SWE in 2011 was over three times that of 2012, at 51.6” of water content, and occurred on May 6th.



SWE accumulation and ablation for Water Years 2011 and 2012, with dust-on-snow events shown, by date, as brown bars for both water years (as observed at the Senator Beck Basin Study Area).

During WY 2011 eleven dust events occurred at Senator Beck Basin containing a total of 14 grams of dust per square meter. Most of those major dust layers were found in CODOS snow profiles that season at the Rabbit Ears Pass CODOS site. However, relentless accumulation of late winter and spring snow routinely buried new dust layers and restored high snow albedo values throughout April and May, until the final and perhaps largest event of the season on May 29th.

Last season, during WY 2012, a similar twelve dust events occurred at Senator Beck Basin containing a total of ~10-12 grams of dust per square meter (see Senator Beck Basin Summary – Dust Log discussion). But, in a dramatic switch, late winter and spring 2012 were exceptionally dry, with widely spaced and comparatively small winter storms (see Senator Beck Basin – Winter Storm Log Discussion) leaving dust exposed at the snowpack surface for extended periods, beginning in early March.

In our March 15th snow profile at our Rabbit Ears Pass CODOS site, we found event D4 dust at the surface of the 153 cm (60”) snowpack, with 6 cm of slushy, melt/freeze polycrystals at the snowpack surface. The snowpack retained minimal cold content on this date, with a mean snowpack temperature of -1.0° C. Total SWE in our CODOS site snowpit was 490 mm (19.3”), versus 15.0” at the Rabbit Ears Snotel site (just below its peak SWE of 15.2”, two days earlier).

By April 10th, our next snow profile at Rabbit Ears Pass found the diminished 77 cm (30”) snowpack fully isothermal at 0° C, with wet snow forms throughout. Merged dust layers coinciding with events D4-D8 were at the snowpack surface, possibly including a D9 event, unique to this locale. Total SWE had fallen to 319 mm (12.6”). On our final CODOS site visit on May 2nd we found 56 cm (22”) of snow containing 233 mm (9.2”) of SWE still remaining, saturated by rain the evening before, but with merged dust layers D4-D8 still apparent and substantially reducing snow albedo.

Snowpack on Rabbit Ears Pass, in an open meadow at the headwaters of Walton Creek, on May 2nd, **2012** (left) as compared to a year earlier, on June 9, **2011**. This meadow was likely snow-free well before the final D12 dust event of 2012, on May 26th, whereas the final event of spring 2011, D11 on May 29th, fell onto a still very deep snowpack, substantially reducing snow albedo and enhancing snowmelt runoff.

MELT RATE

Rabbit Ears SNOTEL Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Post-Peak Added SWE	Adjusted Daily Mean Loss SWE	Period Mean Temp
WY 2006	4/9/2006	38.0	50	2.3	0.81	4.6
WY 2007	4/14/2007	22.7	37	2.9	0.69	4.9
WY 2008	4/15/2008	38.0	62	8.5	0.75	4.1
WY 2009	4/21/2009	32.8	40	3.8	0.92	5.7
WY 2010	5/16/2010	19.2	22	2.1	0.97	7.9
WY 2011	5/6/2011	51.6	52	5.3	1.09	7.3
Max	5/16	51.6	62	8.5	1.09	7.9
Min	4/9	19.2	22	2.1	0.69	4.1
Range	38	32.4	40	6.4	0.40	3.8

Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE

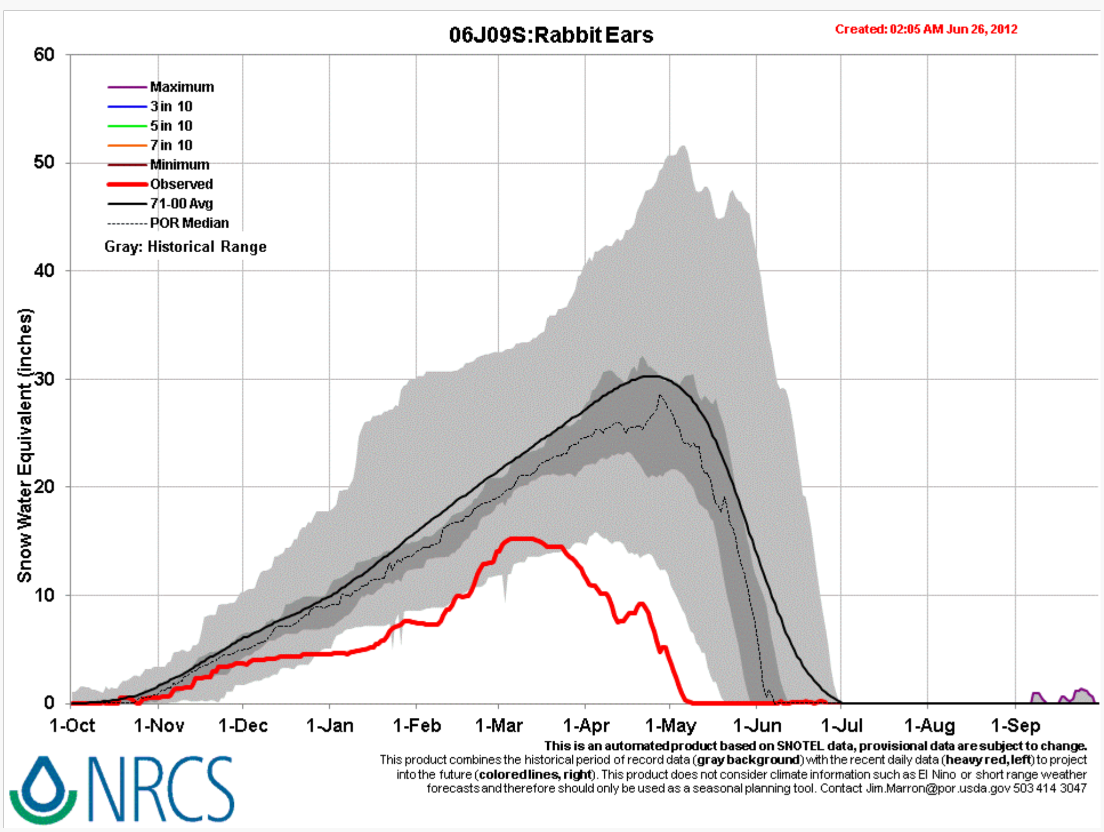
Analysis of Rabbit Ears Pass Snotel data for 2006-2012 snowmelt seasons showing date and quantity of peak SWE, days from peak SWE to “snow all gone” (SAG), total additional precipitation after date of peak SWE, an “adjusted” mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG.

This discussion references CODOS Snotel site data and analyzes rates of snowmelt from Spring 2006 to the present, spanning the period during which we've rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. Since the Snotel network is the only spatially extensive system continuously monitoring snowmelt throughout the Colorado mountains, year-to-year comparisons of Snotel melt rate data may yield insights into dust effects on local watershed-scale processes that our occasional CODOS snowpit measurements can't reveal.

However, as we often note, many Snotel sites exhibit a radiative regime where surrounding trees reduce the access of incoming solar radiation to snowpack over the SWE measuring snow pillow, and where re-radiation of long wave energy from that vegetation and reduced skyview may inhibit radiant cooling and extend surface snowmelt during nighttime hours. The Rabbit Ears Pass Snotel site exhibits these attributes and, as a consequence, does not experience the maximum effects of dust reductions in snow albedo, and short-wave radiative forcing, as compared to the nearby open meadow and our CODOS snowpit site where solar access is comparatively unimpeded, until the sun is low in the western sky. This difference in dominant radiation regimes (long-wave in shady forests versus short-wave in sunny, open terrain) is routinely seen where snow-free open meadows immediately adjoin forest retaining snowcover.

A view of the Rabbit Ears Pass Snotel site approach SAG on May 2nd, 2012. This site has a slightly southwestern aspect. Although part of the snow pillow has melted open (closest to the camera), 14" of snow containing 3.0" of SWE were still being measured over the remainder of the pillow. A small clearing in the forest just beyond the Snotel had lost all snowpack. Our CODOS site, which slopes 4 to the north-northwest, still had 56 cm (22") of snow containing 233 mm (9.2") of SWE on this date.

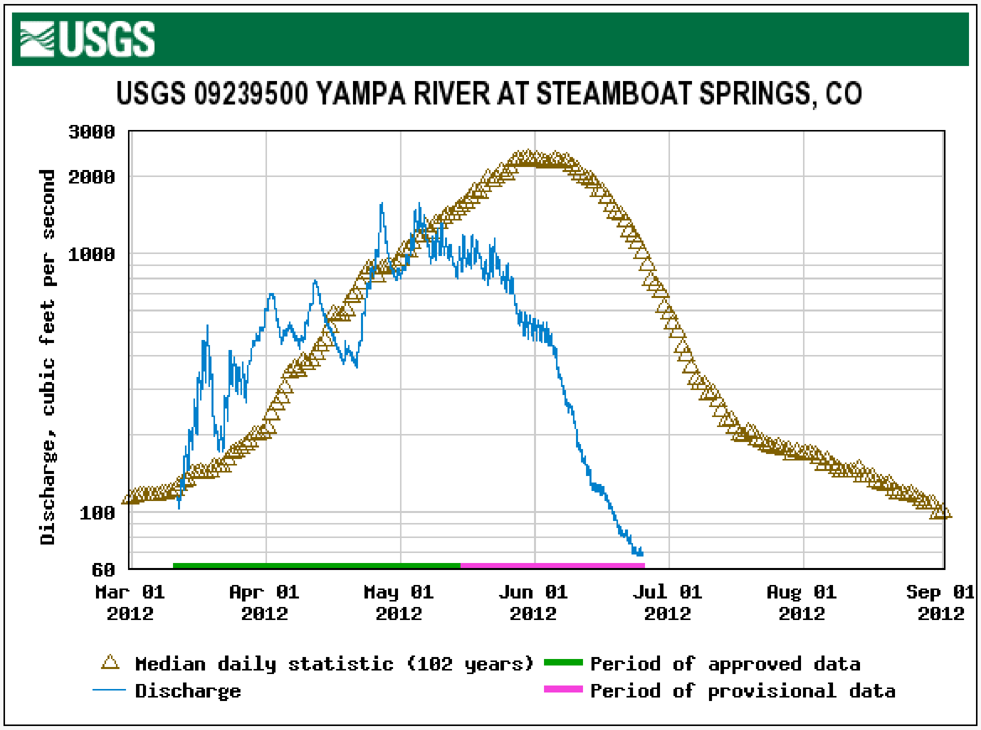
During WY 2012, three fall and early winter dust storms were observed low in the snowpack at Senator Beck Basin, and at least one of these layers (likely D3) was discernible at Rabbit Ears Pass in our CODOS snow profiles. Later, dust-on-snow events D9-D12 may have had little effect in the Rabbit Ears Pass locale, as very little snowpack was left in open terrain at these sub-alpine elevations. Where snowpack did persist into late May at higher elevations farther north in the Park Range, events D9-12 likely did reduce snow albedo and enhance late-season snowmelt runoff rates.



WY 2012 SWE accumulation and ablation at Rabbit Ears Pass Snotel with upper and lower quartiles of period of record shown in light grey, middle quartiles in dark grey surrounding median trace for period of record, and mean trace for 1971-2000 period.

Because of the early date of WY 2012 peak SWE at Rabbit Ears Pass Snotel, on March 13th, spring 2012 produced a two-step descending limb in the SWE plot rather than the single, steep plunge following the very delayed peak SWE in 2011. In 2012, snowpack ablation gradually accelerated in mid-March until storms in mid-April produced a small rebound in SWE. Then, in late April, under the influence of unseasonably warm temperatures and further reductions in snow albedo from dust, melt rates accelerated again. Overall, the Rabbit Ears Pass Snotel site required 52 days to ablate 19.6" of SWE (including 4.4" of precipitation after peak SWE), averaging 0.34" of SWE loss per day.

STREAM FLOWS



WY 2012 USGS Yampa River at Steamboat Springs Stream Gauge data for a 568 sq. mi. drainage area in the upper Yampa River watershed, above 6,695'. Current year and historic data reflect upstream trans- and in-basin diversions for irrigation and for water storage in five reservoirs.

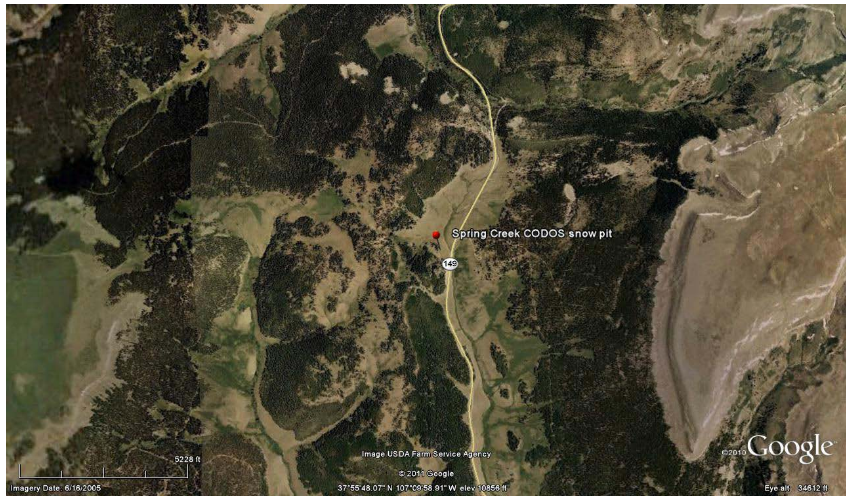
Given the very dry spring and sub-par snowpacks throughout the Northern mountains, below average snowmelt runoff in the Yampa River watershed was unsurprising. The Yampa River at Steamboat Springs hydrograph shows an early start to runoff with substantially above-average flows in March and early April to a peak in late April. An additional surge in early May was followed by a gradually accelerating decline in flows. As was typical throughout the state, by the end of June streamflows had fallen below levels expected two months later, in September.

In addition to the very warm temperatures associated with prolonged periods of dry and sunny weather in late winter and spring 2012, dust-on-snow events D4 (March 6th) and D8 (April 6th) played a role in this early Yampa River runoff, reducing snow albedo and hastening the ripening of the snowpack in late March, to isothermal. Dust then continued absorbing and adding solar energy to the snowmelt energy budget during subsequent periods of exposure at the snowpack surface in April and May. Additional dust events in late May, and perhaps particularly D12 on May 26th, further reduced snow albedo in the scant remaining high elevation snowpack in the Park Range, Flattops, and Elkhead Mountains, hastening the final drying of streams emanating from these Northern mountain systems.

CODOS Water Year 2012 Updates > 2012 Summary > Spring Creek Pass

WATER YEAR 2012 CODOS SUMMARY FOR SPRING CREEK PASS

Summary | Snowpack & Dust | Melt Rates | Stream Flows

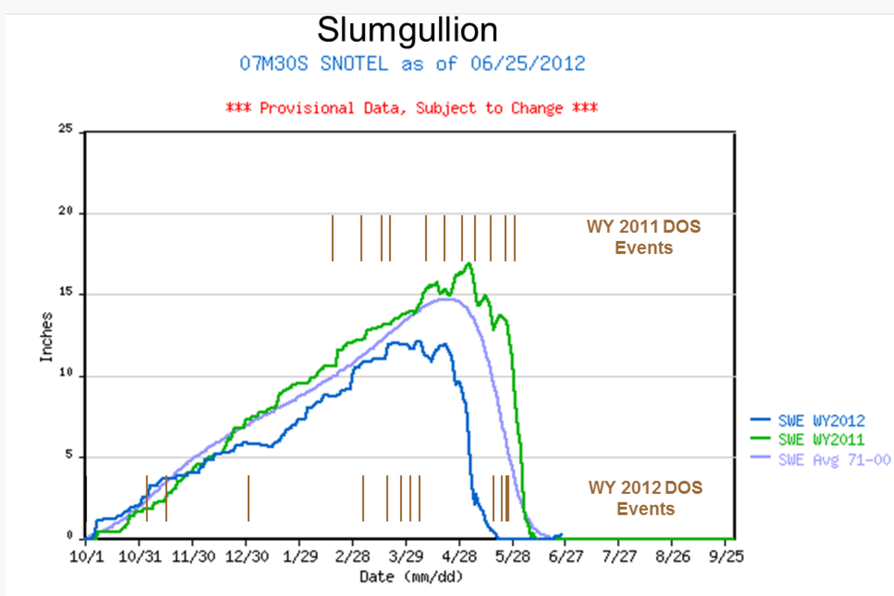


SUMMARY

Water Years 2011 and 2012 are a case study in interannual variability of Colorado snowpack formation and ablation driven by vastly different late winter and spring weather conditions, perhaps representing seasonal extremes. In dramatic contrast with the endless storms and tremendous snowpacks of Mar/Apr/May 2011, extremely dry late-winter and spring weather in 2012 resulted in very low values of peak SWE, very early in the spring, in the headwaters of the Rio Grande River.

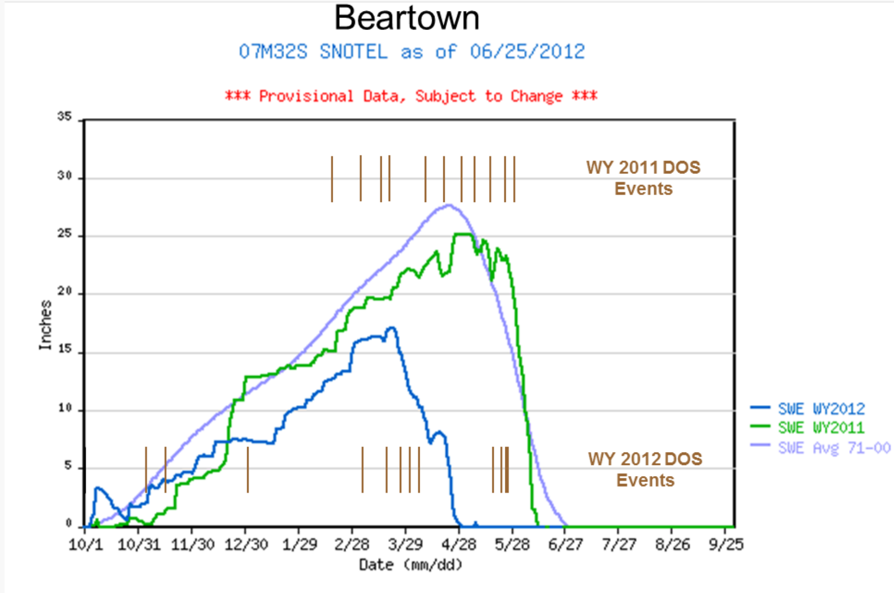
On the other hand, the past two seasons produced comparatively smaller differences in dust-on-snow conditions, with WY 2012 coming close to matching WY 2011 at the Senator Beck Basin Study Area, our baseline monitoring site. Spring 2012 snowpack ablation at the CODOS Spring Creek Pass snowpit site was extremely rapid. In mid-March, dust-on-snow layer D4 was initiating snowpack warming at both the Spring Creek Pass and Wolf Creek Pass CODOS snowpit sites. Three weeks later, on April 9th the Spring Creek Pass site was effectively “snow all gone” (SAG), the Wolf Creek Summit CODOS site had lost nearly half of its SWE, and Rio Grande snowmelt runoff was accelerating well in advance of long-term average timing. Despite a sequence of high amplitude surges, peak flows fell short of average before a steep decline began in late May, reaching very low, late summer flows by the end of June. Overall, the Rio Grande WY 2012 snowmelt runoff hydrograph at Del Norte was advanced several weeks ahead of the period of record median timing, with an unusually steep descending limb.

SNOWPACK & DUST



Water Year 2012 snowpack formation at several Rio Grande watershed Snotel sites began well, with near-average snow accumulations at Slumgullion and Wolf Creek Pass on the north and south. Beartown began falling behind average SWE first before SWE accumulation stalled at all sites in mid-late December. Subsequently, Slumgullion Pass came closest to recovering and fell just short of average SWE before peaking in mid-March. Beartown and Wolf Creek Summit peaked very near the lower quartile of values for March. Due to the very dry late-winter and spring experienced throughout Colorado, WY 2012 peak SWE at Slumgullion Pass was only 12.1”, short of the 1971-2000 average of 14.7” and far short of the 16.9” peak of 2011. Peak SWE 2012 also occurred early in the season, on April 6th, seventeen days earlier than the 1971-2000 average of April 22nd and almost a month earlier than Peak SWE 2011, on May 4th.

Near the headwaters, the Beartown Snotel recorded a larger but earlier WY 2012 peak SWE of 17.1” on March 23rd. To the south, the Wolf Creek Summit Snotel peaked at 29.7” on March 25th. Although WY 2012 peak SWE at Slumgullion Pass fell near the median SWE for that day in the period of record, the subsequent dry weather resulted in SWE falling into the lower quartile of values for the remainder of the season (see Snotel projection plot below). Peak SWE at Beartown (projection plot) occurred very near the lower quartile of values there, and thereafter the snowpack fell further into that lower quartile, ending with SAG earlier than any prior date in the period of record. Wolf Creek Summit (projection plot) experienced a similar pattern but SAG was within the period of record there. Of all three of these Snotel sites, Slumgullion Pass exhibited less overall variation between WY 2011 and 2012 than Beartown and Wolf Creek Summit, but the WY 2012 snowpack at Slumgullion was still well below par.



SWE accumulation and ablation for Water Years 2011 and 2012, with dust-on-snow events shown, by date, as brown bars for both water years (as observed at the Senator Beck Basin Study Area).

During WY 2011 eleven dust events occurred at Senator Beck Basin containing a total of 14 grams of dust per square meter. Most or all of those events were found in CODOS snow profiles in the Rio Grande watershed. However, relentless accumulation of late winter and spring snow routinely buried new dust layers and restored high snow albedo values throughout the State, throughout April and May.

During WY 2012 a similar twelve dust events occurred at Senator Beck Basin containing a total of ~10-12 grams of dust per square meter (see Senator Beck Basin Summary – Dust Log discussion). But, in a dramatic switch, late winter and spring 2012 were exceptionally dry, with widely spaced and comparatively small winter storms (see Senator Beck Basin – Winter Storm Log Discussion). WY 2012 dust layers and reductions in snow albedo in the Rio Grande watershed were similar to those observed in the Senator Beck Basin Study Area.

In our March 17th snow profile at Spring Creek Pass, we found event D4 dust at the snowpack surface, reducing snow albedo and generating surface melt. Nonetheless, this extremely weak snowpack, which repeatedly collapsed during our approach, retained some cold content, with a mean snowpack temperature of -1.6° C. By our return on April 9th, the Spring Creek Pass CODOS site retained only disconnected patches of thin snow, on the verge of SAG. Almost 7” of SWE had been melted in the three weeks between site visits, with dust layer D4 at the surface for most of that period.


CSAS field assistant Andrew Temple returning to the car after completing our March 17th snowpit at the Spring Creek Pass CODOS site. The shallow snowpit can be seen in the distance near the left edge of the photo, below the forest edge.


Spring Creek Pass CODOS snowpit site on the distant slope on April 9th, 2012. At lower elevations, much of the March snowpack had also disappeared.

Views of the Brown Lakes on March 17th (left) and April 9th (right) in spring 2012 showing the considerable loss of snowpack.

MELT RATE

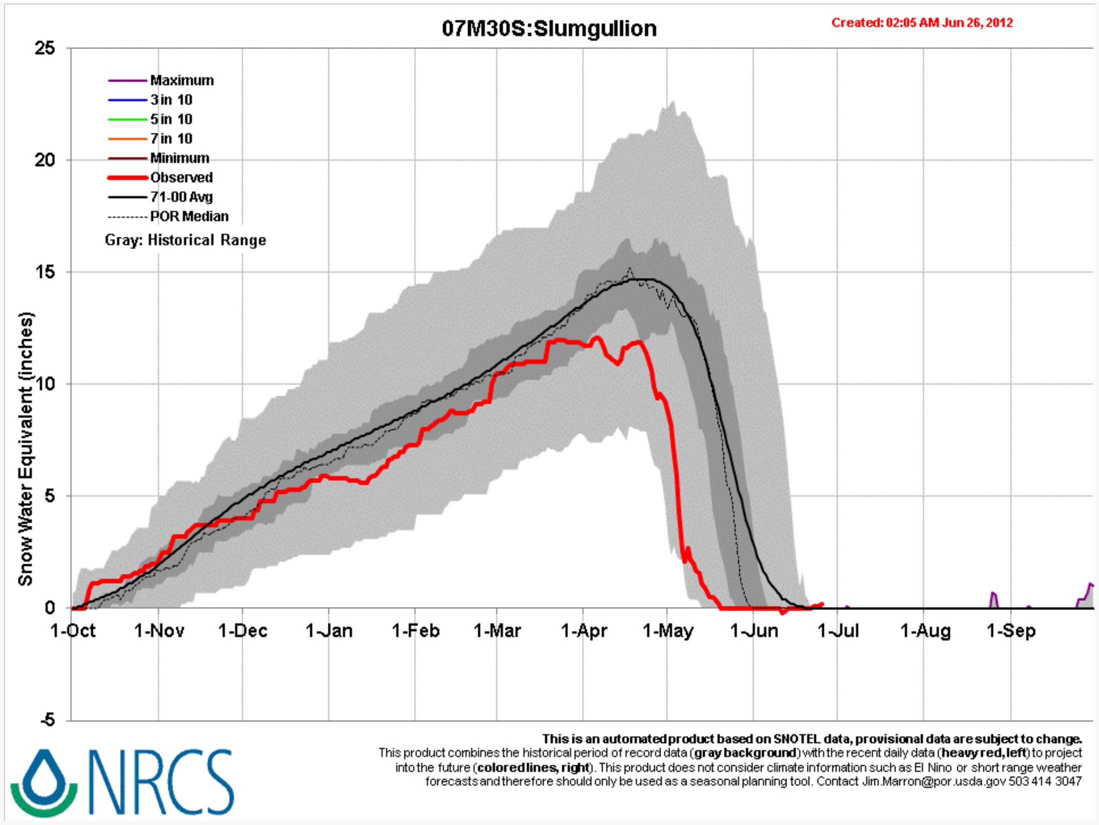
Slumgullion Pass Snotel Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Period Add Precip	Period Mean Temp C	Adjusted Daily Mean Loss SWE	Maximum 5-Day Moving Average of Daily Loss of SWE	SBBSA DOS Post Peak SWE
WY 2006	4/17/2006	15.9	38	0.4	2.2	0.43	1.0	2
WY 2007	4/18/2007	16.6	50	3.6	3.3	0.40	1.1	3
WY 2008	4/20/2008	19.6	49	2.3	2.9	0.45	1.2	3
WY 2009	4/21/2009	16.0	27	0.4	4.5	0.61	1.2	2
WY 2010	4/11/2010	14.7	45	2.6	1.1	0.38	1.1	5
WY 2011	5/4/2011	16.9	35	2.1	4.1	0.54	1.3	4
WY 2012	4/6/2012	12.1	43	2.0	3.1	0.33	1.2	4
Max	05/04/11	19.6	50	3.6	4.5	0.6	1.3	5
Min	04/06/12	12.1	27	0.4	1.1	0.3	1.0	2
Range	28	7.5	23	3.2	3.4	0.3	0.2	3

Analysis of Slumgullion Pass Snotel data for 2006-2012 snowmelt seasons showing date and quantity of peak SWE, days from peak SWE to "snow all gone" (SAG), total additional precipitation after date of peak SWE, an "adjusted" mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG.

This discussion references CODOS Snotel site data and analyzes rates of snowmelt from Spring 2006 to the present, spanning the period during which we've rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. As discussed in prior CODOS Updates, many Snotel sites, including Slumgullion Pass, exhibit a radiative regime where surrounding trees reduce the access of incoming solar radiation to snowpack over the SWE measuring snow pillow, and where re-radiation of long wave energy from that vegetation and reduced skyview may inhibit radiant cooling and extend surface snowmelt during nighttime hours. As a consequence, Snotel sites often do not experience the maximum effects of dust-on-snow on snowmelt timing and rates, as compared to generally level, open meadow sites where solar access is unimpeded and snowmelt energy budgets and snowpack ablation are measured. Nonetheless, the Snotel network is the only spatially extensive system monitoring snowmelt throughout the Colorado mountains and year-to-year comparisons of Snotel melt rate data may yield insights into dust effects on local watershed-scale processes.

During WY 2012, three fall and early winter dust storms were observed low in the snowpack at Senator Beck Basin, but none of these layers was discernible in the Spring Creek Pass snowpack. And, although several dust-on-snow events fell after the date of SAG at Spring Creek Pass in WY 2012, those later events did nonetheless further reduce snow albedo and enhance snowmelt rates in the remaining snowpack at higher elevations and on shady subalpine aspects in the nearby terrain in the Rio Grande River basin.



WY 2012 SWE accumulation and ablation at Slumgullion Pass Snotel, with upper and lower quartiles of period of record shown in light grey, middle quartiles in dark grey surrounding median trace for period of record, and mean trace for 1971-2000 period.

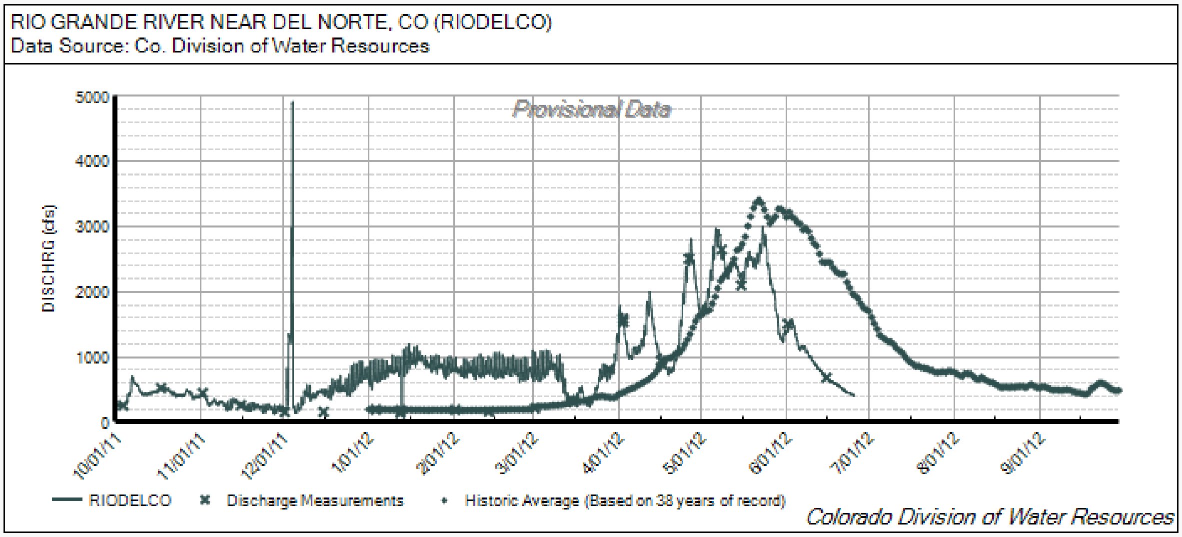
Because of the comparatively early date of WY 2012 peak SWE at Slumgullion Pass Snotel, on April 6th, spring 2012 produced a two-step descending limb in the SWE plot rather than the single, very steep plunge following the second peak SWE in 2011. In 2012, snowpack ablation made a false start in March before a rebound in SWE from new snow in mid-month (Storm #20 – see Senator Beck Basin Storm Log discussion). Melt resumed following peak SWE (D8 also fell on April 6th) before another interruption by additional snowfall midmonth. Snowmelt accelerated sharply as dust event D8 re-emerged and merged with underlying dust for the remainder of the melt cycle.

The upper Rio Grande headwaters as seen from Stony Pass on May 19th, 2012. This rare mid-May opening of the Stony Pass road opening was possible because of the season's sub-par snowpack and early snowmelt cycle. Dust-on-snow conditions at Stony Pass closely resembled those observed at Senator Beck Basin at the time.

As seen in the Slumgullion Pass Snotel melt rate table above, Spring 2012 produced the lowest value and earliest date of Peak SWE in the past seven years yet still required more days to fully ablate the snowpack (43) than were required to melt the much larger snowpack the year before, in 2011. Since 2006, WY 2012 experienced the lowest rate of daily SWE loss (0.33" per day) for the full snowmelt period whereas 2011 melt rates were among the highest at Slumgullion Pass. The entire WY 2012 snowmelt cycle remained just within the historic range of snowmelt timing in the Slumgullion Pass period of record.

Some 42 miles to the southeast on the southern edge of the Rio Grande basin, the Wolf Creek Summit Snotel (also heavily shaded by adjoining forest) also experienced snowmelt within the lower quartile of the period of record. And, about 24 miles to the southwest of Slumgullion Pass, at the Rio Grande headwaters, Beartown Snotel immediately attained and sustained, apart from a mid-April storm rebound, a comparatively high snowmelt rate following peak SWE in late March, averaging 0.5" of SWE loss per day over the 38 days to SAG. The Beartown Snotel is just some 18 miles southeast of the Senator Beck Basin Study Area and the scant snowpack in the upper Rio Grande headwaters closely resembled Senator Beck Basin in spring 2012.

STREAM FLOWS



WY 2012 Rio Grande River near Del Norte Stream Gauge data for a 1,320 sq. mi. drainage area in the upper Rio Grande River watershed, above 7,980'.

Streamflow data from the Rio Grande River at Del Norte gauge presents an early and erratic ascending limb followed by a very rapid descending limb of snowmelt runoff in WY 2012. Unseasonably warm and dry weather combined with gradually increasing reductions in snow albedo by dust in March and April produced streamflows surging to several times average discharge levels in late March, April and early May, and retreating to average flow levels between surges. Discharge intersected with median levels in mid May, between nearly identical below-average peaks in flow bracketing a normal date of peak flow. The decline in flows between the two peaks may be explained by an upslope precipitation event originating in eastern Colorado delivering over an inch of precipitation as far west as Wolf Creek Summit, restoring a higher snow albedo to at least the eastern portion of the remaining snowpack in the watershed. Following the second peak in discharge, as the scant snowpack remaining at only higher elevations was rapidly consumed, steep declines in discharge resulted in flows on July 1st not normally seen until September.

Given the below-average snowpack, a reduction in snowmelt runoff yield is unsurprising. However, the Rio Grande hydrograph also presents a substantial advance in the timing of WY 2012 runoff, with the center of runoff mass once again occurring several weeks earlier than normal. In addition to the very warm temperatures associated with prolonged periods of dry and sunny weather, dust-on-snow was also factor in this early and highly erratic runoff, hastening the "ripening" of the snowpack in March, to isothermal, and then absorbing and adding additional solar energy to the snowmelt energy budget in April and the remainder of the unusually dry spring season.

CODOS SUMMARY FOR WILLOW CREEK PASS

Summary | Snowpack | Melt Rate | Stream Flows

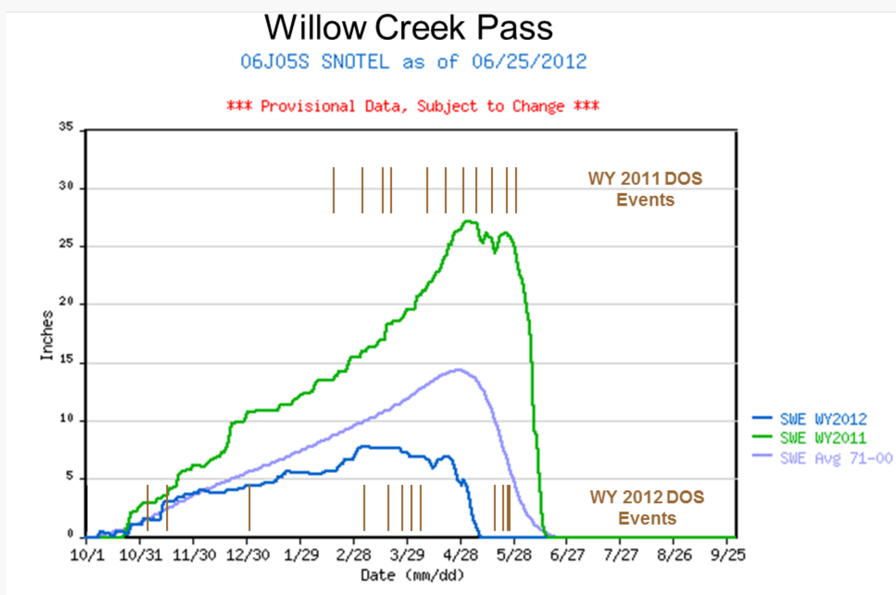
SUMMARY

Water Years 2011 and 2012 are a case study in interannual variability of Colorado snowpack formation and ablation driven by vastly different late winter and spring weather conditions, perhaps representing seasonal extremes. In dramatic contrast with the unrelenting storms of Mar/Apr/May 2011, extremely dry late-winter and spring weather in 2012 resulted in low values of peak SWE, very early in the spring.

On the other hand, the past two seasons produced comparatively smaller differences in dust-on-snow conditions, with WY 2012 coming close to matching WY 2011 at the Senator Beck Basin Study Area, our baseline monitoring site. Following the extremely early date of peak SWE, on March 8th, mid-March 2012 desert dust concentrations in the Willow Creek Pass locale were similar to those observed at Grizzly Peak and Berthoud Summit and the Willow Creek Pass CODOS site snowpack was isothermal in mid-March. Snowmelt then rapidly accelerated and the CODOS site was "snow all gone" (SAG) before April 10th, our next site visit. Streamflow data from the Willow Creek above Willow Creek Reservoir gauge show high flows when the gauge was activated in early April, peak flow in late April, and a very steep descending limb for what was an apparently compressed runoff cycle.

SNOWPACK DISCUSSION

Water Year 2012 snowpack formation at the Willow Creek Pass Snotel site began well. Then, in early December, snowpack accumulation began to lag and by mid-December SWE accumulations had fallen into the lower quartile of SWE values for the period of record where they remained until April (see Snotel projection plot below). Peak SWE occurred very early, on March 8th, at just 7.7", well short of the 1971-2000 average of 14.3" and seven weeks earlier than the April 27th average date of peak SWE. Peak SWE in 2011 was 27.1" and occurred on May 4th. On/about April 1st SWE values fell below any prior measured values in the period of record for a short period before just returning to the lowest quartile of values.



SWE accumulation and ablation for Water Years 2011 and 2012, with dust-on-snow events shown, by date, as brown bars for both water years (as observed at the Senator Beck Basin Study Area).

During WY 2011 eleven dust events occurred at Senator Beck Basin containing a total of 14 grams of dust per square meter. Most of those major dust layers were found in CODOS snow profiles that season at the Willow Creek Pass CODOS site. However, relentless accumulation of late winter and spring snow routinely buried new dust layers and restored high snow albedo values throughout April and May, until the final and perhaps largest event of the season on May 29th.

Last season, during WY 2012, a similar twelve dust events occurred at Senator Beck Basin containing a total of ~10-12 grams of dust per square meter (see Senator Beck Basin Summary – Dust Log discussion). But, in a dramatic switch, late winter and spring 2012 were exceptionally dry, with widely spaced and comparatively small winter storms (see Senator Beck Basin – Winter Storm Log Discussion) leaving dust exposed at the snowpack surface for extended periods, beginning in early March.

In our March 15th snow profile at our Willow Creek Pass CODOS site, we found dust layer D4 at the surface of the shallow, 74 cm (29") snowpack, in wet melt/freeze polycrystal forms. The snowpack retained virtually no cold content on this date and was effectively isothermal, with a mean snowpack temperature of -0.1° C. This snowpack was extremely weak and our team produced massive snowpack collapses in this open meadow upon approaching the site.

By our next site visit on April 10th, the Willow Creek Pass CODOS site was snow-free. A year earlier, on April 24th, 2011 the snowpack at this site was 126 cm (50") deep and the Snotel site was still approaching peak SWE.

The long-since snow-free Willow Creek Pass CODOS snowpit site on April 9th, **2012** and over a month later in the prior season, on May 17th, **2011**, still with an 88 cm (35") deep snowpack.

MELT RATE

Willow Creek Pass Snotel Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Period Add Precip	Period Mean Temp C	Adjusted Daily Mean Loss SWE	Maximum 5-Day Moving Average of Daily Loss of SWE
WY 2006	4/27/2006	13.4	28	0.8	3.8	0.51	1.10
WY 2007	4/28/2007	16.8	37	1.7	4.5	0.50	0.94
WY 2008	5/16/2008	21.9	30	2.0	5.8	0.80	1.14
WY 2009	4/20/2009	14.7	37	3.4	4.8	0.49	0.94
WY 2010	5/16/2010	14.4	21	0.5	6.6	0.71	1.16
WY 2011	5/4/2011	27.1	43	3.8	5.4	0.72	2.40
WY 2012	3/8/2012	7.7	55	1.7	1.9	0.17	0.42
Max	05/16/08	27.1	55	3.8	6.6	0.8	2.4
Min	03/08/12	7.7	21	0.5	1.9	0.2	0.4
Range		19.4	34	3.3	4.7	0.6	2.0
Median		14.7	37	1.7	4.8	0.5	1.1

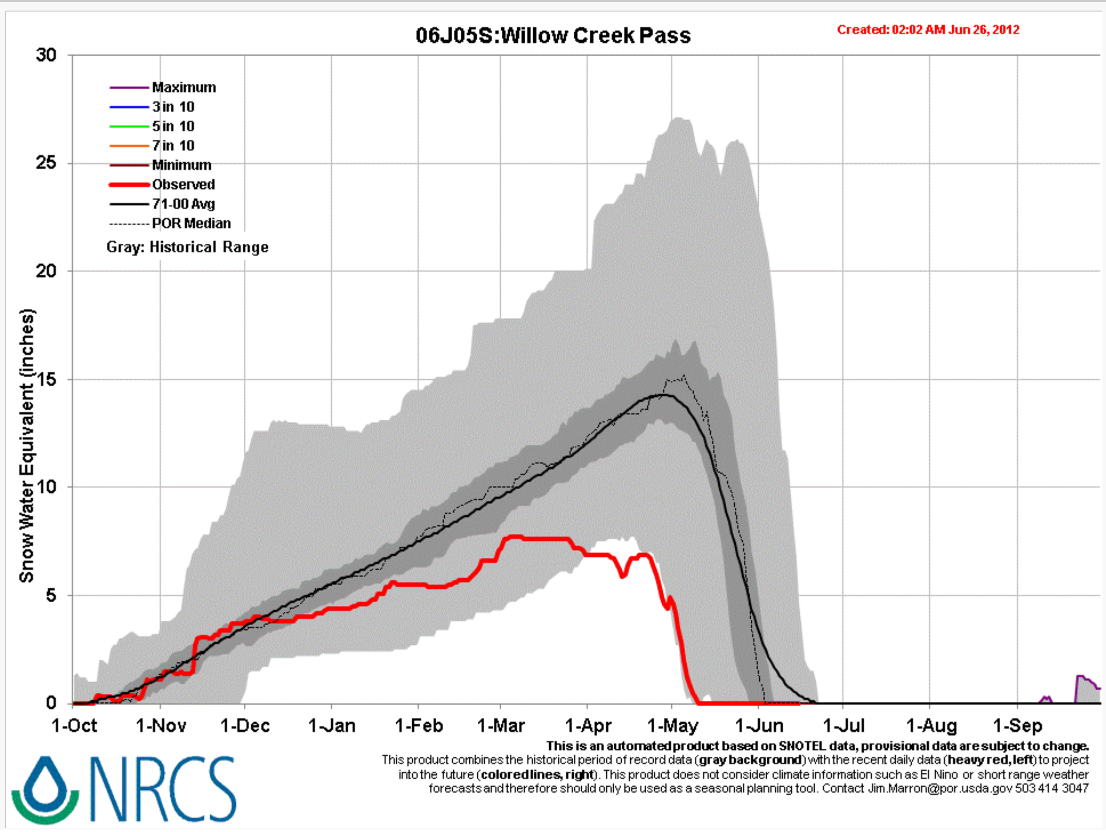
Analysis of Willow Creek Pass Snotel data for 2006-2012 snowmelt seasons showing date and quantity of peak SWE, days from peak SWE to "snow all gone" (SAG), total additional precipitation after date of peak SWE, an "adjusted" mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG.

This discussion references CODOS Snotel site data and analyzes rates of snowmelt from Spring 2006 to the present, spanning the period during which we've rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. Since the Snotel network is the only spatially extensive system continuously monitoring snowmelt throughout the Colorado mountains, year-to-year comparisons of Snotel melt rate data may yield insights into dust effects on local watershed-scale processes that our occasional CODOS snowpit measurements can't reveal.

However, as we often note, many Snotel sites exhibit a radiative regime where surrounding trees reduce the access of incoming solar radiation to snowpack over the SWE measuring snow pillow, and where re-radiation of long wave energy from that vegetation and reduced skyview may inhibit radiant cooling and extend surface snowmelt during nighttime hours. Although beetle kill has perhaps reduced the surrounding forest's density since our 2008 photo below, the Willow Creek Pass Snotel site is still shaded by trees to the south and, as a consequence, does not experience the maximum effects of dust reductions in snow albedo, and short-wave radiative forcing, as compared to the adjacent open meadow and our CODOS snowpit site where solar access is comparatively unimpeded. This difference in dominant radiation regimes (long-wave in shady forests versus short-wave in sunny, open terrain) is routinely seen where snow-free open meadows immediately adjoin forest retaining snowpack.

A view of the Willow Creek Pass Snotel site looking south on April 17th, 2008. Although beetle kill may have further reduced the density of this tree cover, some shading of the snow pillow is still reducing the influence of dust on snowmelt rates at this site.

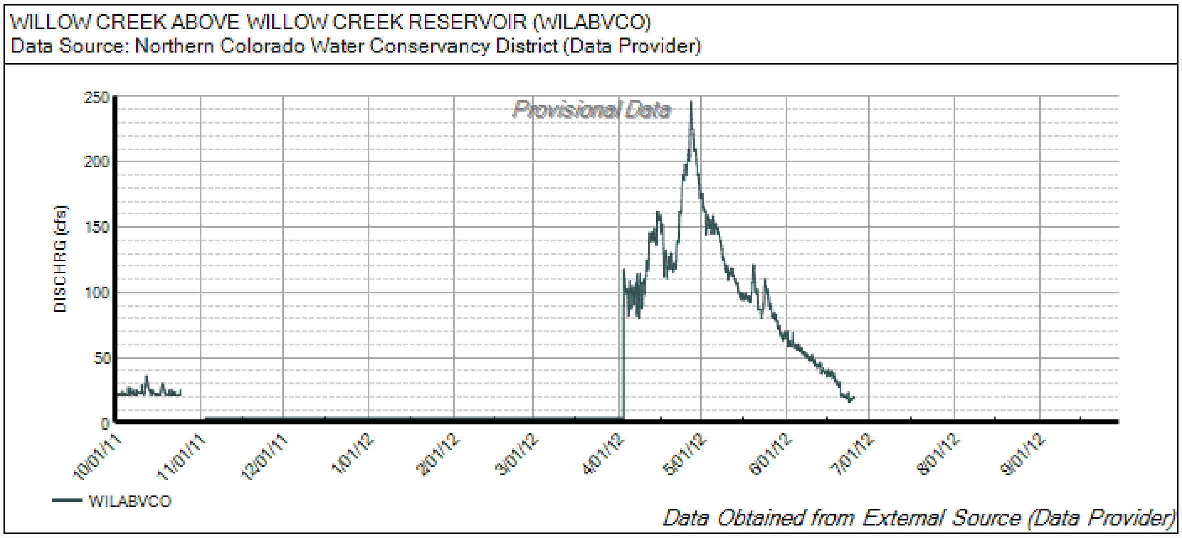
During WY 2012, three fall and early winter dust storms were observed low in the snowpack at Senator Beck Basin, but none of these layers were discernible at Willow Creek Pass in our CODOS snow profiles. And, although dust-on-snow events D8-D12 fell after the date of SAG at our Willow Creek Pass CODOS site in WY 2012, those later events further reduced snow albedo and enhanced snowmelt rates in the remaining snowpack at higher elevations and on shady subalpine aspects in the nearby terrain.



WY 2012 SWE accumulation and ablation at Willow Creek Pass Snotel with upper and lower quartiles of period of record shown in light grey, middle quartiles in dark grey surrounding median trace for period of record, and mean trace for 1971-2000 period.

Because of the early date of WY 2012 peak SWE at Willow Creek Pass Snotel, on March 8th, spring 2012 produced a two-step descending limb in the SWE plot rather than the single, steep plunge following the very delayed peak SWE in 2011. In 2012, snowpack ablation at this Snotel site gradually accelerated in late March and early April until mid-April storms produced a small rebound in SWE. Then, in late April, under the influence of unseasonably warm temperatures and reductions in snow albedo, primarily from dust layer D4, melt rates accelerated a second time, to a much higher rate. Overall, the Willow Creek Pass Snotel site required some 55 days to ablate 9.4" of SWE (including 1.7" of precipitation after peak SWE), averaging just 0.17" of SWE loss per day.

STREAM FLOWS



WY 2012 stream gauge data Willow Creek above Willow Creek Reservoir. Data are provided by Northern Water Conservancy District. No additional station information is available and median flow data for the period of record at this gauge are not included in the hydrograph provided.

Given the very dry spring and sub-par snowpacks throughout the Front Range and Northern Colorado mountains, below average snowmelt runoff in those watersheds was unsurprising. Although the Willow Creek hydrograph above does not include historic flow level data, the plot may show evidence of an early start to a high-amplitude but compressed runoff cycle, with substantially above-average flows in April and an early peak in late April. Runoff immediately began a very rapid decline in early May to levels in late June that appear to match late fall 2011 base flows.

In addition to the very warm temperatures associated with prolonged periods of dry and sunny weather in late winter and spring 2012, dust-on-snow event D4 (March 6th) played a role in this apparently early Willow Creek runoff, reducing snow albedo and hastening the ripening of the snowpack in mid-March, to isothermal. Dust then continued absorbing and adding solar energy to the snowmelt energy budget during subsequent periods of exposure at the snowpack surface in early April, up to SAG. Additional dust events later in April and May, particularly D8 on April 6th and D12 on May 26th, further reduced snow albedo in the scant remaining high elevation snowpack in this locale and rapidly drying streams fed by Rabbit Ears Range snowmelt.

WATER YEAR 2012 CODOS SUMMARY FOR WOLF CREEK PASS

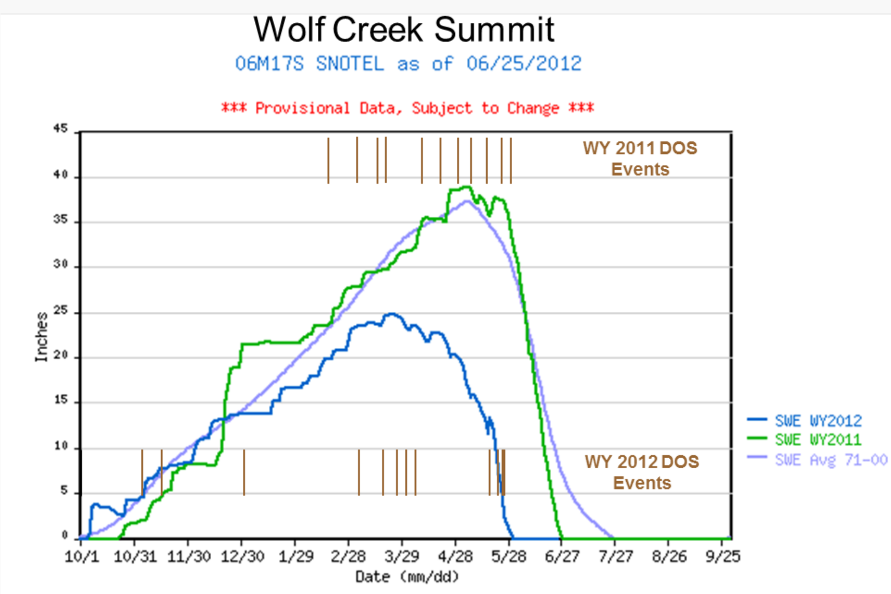
Summary | Snowpack | Melt Rate | Stream Flows

SUMMARY

Water Years 2011 and 2012 are a case study in interannual variability of Colorado snowpack formation and ablation driven by vastly different late winter and spring weather conditions, perhaps representing seasonal extremes. In dramatic contrast with the endless storms of Mar/Apr/May 2011, extremely dry late-winter and spring weather in 2012 resulted in low values of peak SWE, very early in the spring, in the headwaters of the Rio Grande and San Juan rivers.

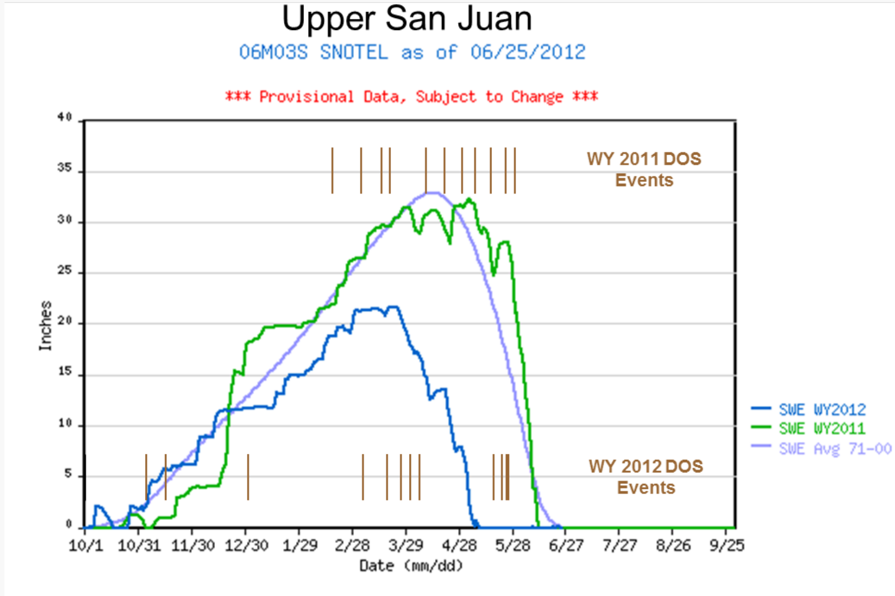
On the other hand, the past two seasons produced comparatively smaller differences in dust-on-snow conditions, with WY 2012 coming close to matching WY 2011 at the Senator Beck Basin Study Area, our baseline monitoring site. Spring 2012 snowpack ablation at the CODOS Wolf Creek Pass snowpit site was rapid, enhanced by dust layers D4-D8. By March 17th, dust-on-snow layer D4 was enhancing snowpack warming at the Wolf Creek Pass CODOS snowpit, already near isothermal. In late March both the San Juan and Rio Grande were recording strong surges in streamflows reaching several times their respective average flows for that period. Three weeks later, on April 9th the Wolf Creek Pass site was isothermal and had lost nearly half of its SWE. Despite a sequence of high amplitude runoff surges in both rivers, peak flows fell short of average before steep declines began in late May, reaching very low, late summer flows by the end of June. Overall, WY 2012 snowmelt runoff in both the San Juan and Rio Grande rivers was advanced several weeks ahead of median timing.

SNOWPACK DISCUSSION



Water Year 2012 snowpack formation at Wolf Creek Pass began very well, with a major October storm enabling the ski area to open immediately thereafter. Then, after remaining near-average through mid-December, snowpack and SWE accumulation at the Wolf Creek Summit and Upper San Juan Snotels stalled in late December, falling to and then remaining somewhat below average until early March, in the second quartile of SWE values for their periods of record (see Snotel projection plot below).

Due to the very dry late-winter and spring experienced throughout Colorado, WY 2012 peak SWE at Wolf Creek Summit was only 24.8", well short of the 1971-2000 average of 37.2" and the 38.9" peak of 2011. Peak SWE 2012 also occurred early in the season, on March 25th, a full six weeks earlier than the 1971-2000 average of May 5th and the day of Peak SWE 2011. Just a few miles west and 800' lower in elevation, the Upper San Juan Snotel recorded a lower WY 2012 peak SWE of 21.7" on March 23rd, also short of the mean of 32.9” and three weeks ahead of the average date of April 13th.



Caption for 2-year Snotel plots: SWE accumulation and ablation for Water Years 2011 and 2012, with dust-on-snow events shown, by date, as brown bars for both water years (as observed at the Senator Beck Basin Study Area). Differences in site characteristics are discussed below (see Melt Rates discussion).

Peak SWE at both Wolf Creek Summit and Upper San Juan Snotels occurred on the boundary between the second and lower quartiles of the period of record and thereafter remained in the lower quartile to “snow all gone” SAG, at both sites.

During WY 2011 eleven dust events occurred at Senator Beck Basin containing a total of 14 grams of dust per square meter. Most or all of those events were found in CODOS snow profiles in the Wolf Creek Pass snowpack. However, relentless accumulation of late winter and spring snow routinely buried new dust layers and restored high snow albedo values throughout the State, throughout April and May.

Last season, during WY 2012 a similar twelve dust events occurred at Senator Beck Basin containing a total of ~10-12 grams of dust per square meter (see Senator Beck Basin Summary – Dust Log discussion). But, in a dramatic switch, late winter and spring 2012 were exceptionally dry, with widely spaced and comparatively small winter storms (see Senator Beck Basin – Winter Storm Log Discussion). WY 2012 dust layers and reductions in snow albedo in the Rio Grande watershed were similar to those observed in the Senator Beck Basin Study Area

In our March 17th snow profile at our Wolf Creek Pass CODOS site, we found dust event D4 at the snowpack surface where it had been reducing snow albedo and generating surface melt for some time, producing a thick layer of melt/freeze polycrystals at the snowpack surface. The snowpack contained 556 mm (21.9”) of SWE but retained very little cold content by this date, with a mean snowpack temperature of -0.7° C.


CSAS field assistant Andrew Temple beginning the 63” deep snowpit at the Wolf Creek Pass CODOS site on March 17th, 2012. Wolf Creek ski are is seen in the distance.


The Wolf Creek Pass CODOS snowpit site approaching SAG on May 1, 2012, with dust layers D3-8 merged at the snowpack surface.

By our return on April 9th, the Wolf Creek Pass CODOS site retained only 320 mm (12.6”) of SWE, having lost 9.3” in 23 days, and was fully isothermal. Dust layers D4-8 had merged at the snowpack surface reducing snow albedo to levels comparable to those observed at Senator Beck Basin the day before, and additional layers of dust would soon merge and further reduce albedo, as seen during the May 1st site visit, on the verge of SAG.

Although the Wolf Creek Summit Snotel site retained 19.8” of SWE contained in 48” of snow on May 1, the downvalley Upper San Juan Snotel, a few miles west and 800’ lower than the Wolf Creek Summit site, had just 7.1” of SWE. The Wolf Creek Summit Snotel site is in dense forest whereas the Upper San Juan site has a few scattered trees, only on its northern flank, leaving the snowpack on the Snotel pillow open to sunlight on the east, south, and west.

The Upper San Juan Snotel site on May 1, 2012 looking south from the Highway 160 shoulder. The Snotel station is circled. This open site experiences direct solar inputs comparable to our CODOS snowpit site at Wolf Creek Pass.

MELT RATE

Wolf Creek Summit Snotel Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Period Add Precip	Period Mean Temp C	Adjusted Daily Mean Loss SWE	Maximum 5-Day Moving Average of Daily Loss of SWE	SBBSA DOS Post Peak SWE
WY 2006	5/1/2006	25.7	40	1.2	7.7	0.67	1.2	2
WY 2007	4/26/2007	32.3	59	5.6	6.5	0.64	1.7	2
WY 2008	4/26/2008	47.5	71	3.7	6.7	0.72	1.6	2
WY 2009	5/6/2009	35.9	49	3.5	7.1	0.80	1.1	0
WY 2010	5/5/2010	37.1	44	1.4	7.1	0.88	2.2	3
WY 2011	5/5/2011	38.9	54	4.5	7.4	0.80	1.5	4
WY 2012	3/25/2012	24.8	63	4.1	4.7	0.46	1.6	7
Max	05/06/09	47.5	71	5.6	7.7	0.9	2.2	7
Min	03/25/12	24.8	40	1.2	4.7	0.5	1.1	0
Range	42	22.7	31	4.4	3.0	0.4	1.1	7

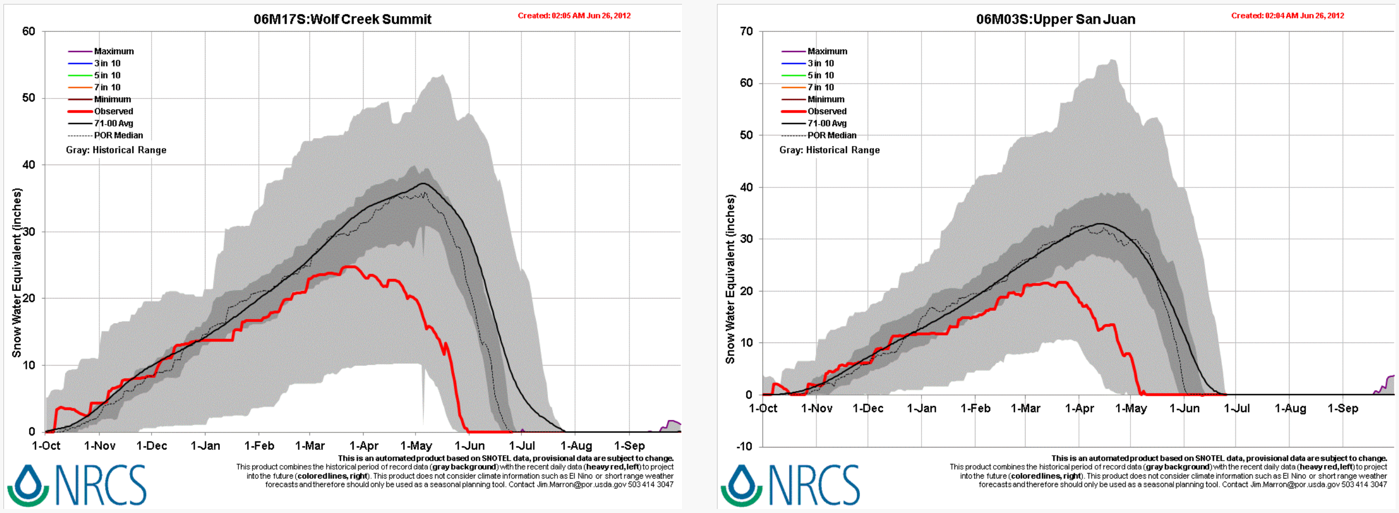
Analysis of Wolf Creek Summit Snotel data for 2006-2012 snowmelt seasons showing date and quantity of peak SWE, days from peak SWE to "snow all gone" (SAG), total additional precipitation after date of peak SWE, an "adjusted" mean daily rate of snowmelt adding the additional precipitation to the peak SWE total, the maximum five-day moving average of daily melt, and the mean air temperature over the entire snowmelt period, from peak SWE to SAG.

This discussion references CODOS Snotel site data and analyzes rates of snowmelt from Spring 2006 to the present, spanning the period during which we've rigorously observed dust-on-snow at our Senator Beck Basin Study Area, at Red Mountain Pass. Since the Snotel network is the only spatially extensive system continuously monitoring snowmelt throughout the Colorado mountains, year-to-year comparisons of Snotel melt rate data may yield insights into dust effects on local watershed-scale processes that our occasional CODOS snowpit measurements can't reveal.

However, as we often note, many Snotel sites exhibit a radiative regime where surrounding trees reduce the access of incoming solar radiation to snowpack over the SWE measuring snow pillow, and where re-radiation of long wave energy from that vegetation and reduced skyview may inhibit radiant cooling and extend surface snowmelt during nighttime hours. The Wolf Creek Summit Snotel site exhibits these attributes and, as a consequence, does not experience the maximum effects of dust reductions in snow albedo, and short-wave radiative forcing, as compared to open meadow sites where solar access is unimpeded and snowmelt and snowpack ablation are measured (e.g., Swamp Angel Study Plot). This difference in dominant radiation regimes (long-wave in shady forests versus short-wave in sunny, open terrain) is routinely seen where snow-free open meadows immediately adjoin forest retaining substantial snowpack.

In contrast to Wolf Creek Summit, the very nearby Upper San Juan Snotel (see photo above) does experience comparatively unimpeded solar access to the east, south, and north, with only scattered trees on its northern flank. The Upper San Juan site is close enough to U.S. Hwy 160 to perhaps experience road dust deposition on occasion. Despite that potential complication, the Upper San Juan site may better capture the radiative impact of desert dust deposition on snowmelt timing and rates in the Wolf Creek Pass locale than the Wolf Creek Summit Snotel site. Hence, both sites are evaluated below.

During WY 2012, three fall and early winter dust storms were observed low in the snowpack at Senator Beck Basin, and some of these layers were discernible at Wolf Creek Pass in our CODOS snow profiles. And, although dust-on-snow events D9-D12 fell after the date of SAG at our Wolf Creek Pass CODOS site in WY 2012, those later events further reduced snow albedo and enhanced snowmelt rates in the remaining snowpack at higher elevations and on shady subalpine aspects in the nearby terrain in the upper Rio Grande and San Juan river basins.



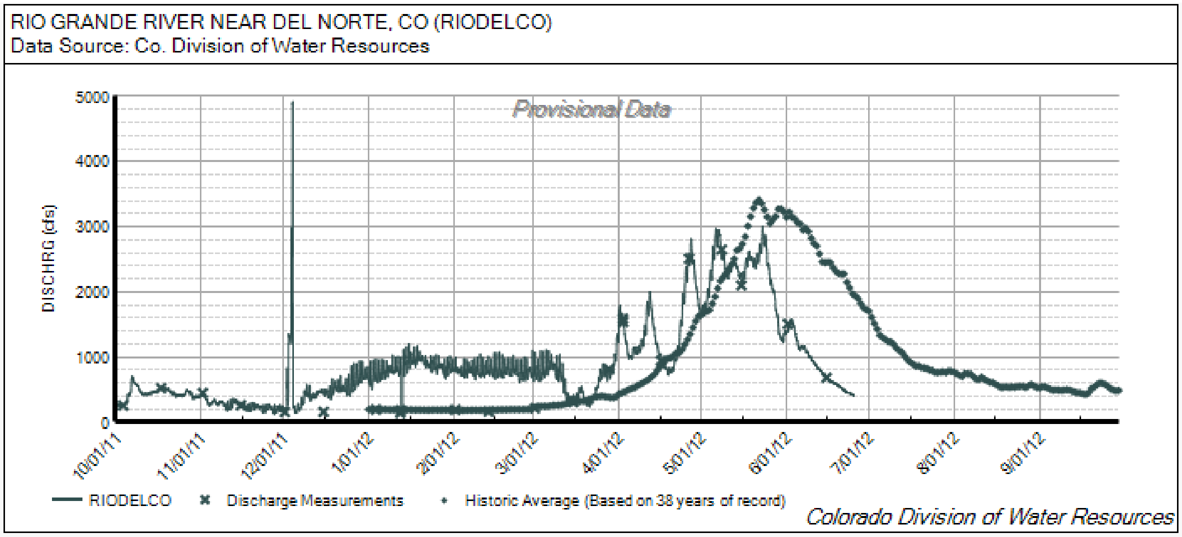
WY 2012 SWE accumulation and ablation at Wolf Creek Summit Snotel and Upper San Juan Snotel, with upper and lower quartiles of period of record shown in light grey, middle quartiles in dark grey surrounding median trace for period of record, and mean trace for 1971-2000 period.

Because of the early date of WY 2012 peak SWE at Wolf Creek Summit Snotel, on March 25th, spring 2012 produced a two-step descending limb in the SWE plot rather than the single, very steep plunge following the very delayed peak SWE in 2011. In 2012, snowpack ablation at Wolf Creek Summit Snotel progressed in fits and starts during April, then accelerated to a higher rate of melt to SAG. Overall, Wolf Creek Summit took 63 days to ablate 28.9" of SWE (including 4.1" of precipitation after peak SWE), averaging 0.46" of SWE loss per day.

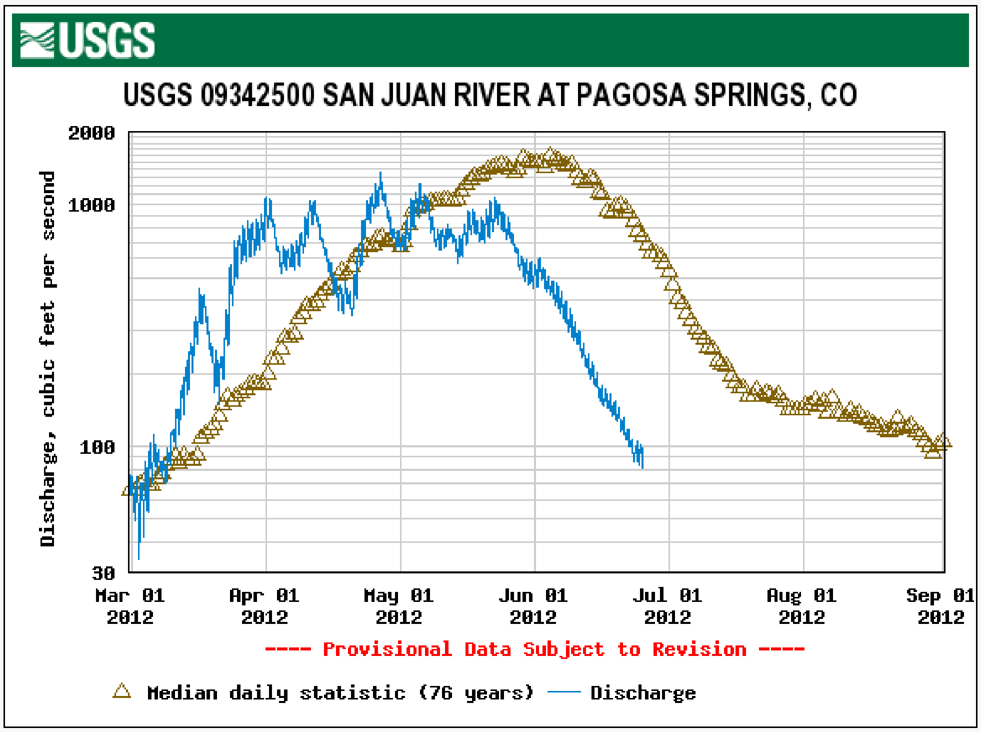
In contrast, melt rates immediately accelerated after peak SWE at the Upper San Juan Snotel with D4 at the snowpack surface. Dust event D8 fell onto already merged layers D4-7 on April 6th, slighly accelerating melt rates until a mid-April storm that restored some SWE and higher snow albedo to the snowpack. Merged dust layers D4-9 quickly re-emerged, dropping albedo and, in tandem with unseasonably warm weather, accelerating melt rates even farther for the duration of snowpack. The entire melt cycle at Upper San Juan, from peak SWE on March 24th to SAG on May 10th, took 47 days to ablate 25.5" of SWE (including 3.8" of precipitation following peak SWE), averaging 0.54" of SWE loss per day, a 17% higher rate than at Wolf Creek Summit. SAG at Upper San Juan was on May 10th, 17 days earlier than SAG at Wolf Creek Summit, on May 27th.

At the north edge of the Rio Grande watershed, the Slumgullion Pass Snotel (heavily shaded) also produced the slowest melt rate (0.33"/day) and lowest value and earliest date of Peak SWE in the past seven years at that site. In the Rio Grande headwaters, Beartown Snotel (only partially shaded) immediately attained and sustained, apart from a mid-April storm rebound, a higher snowmelt rate following peak SWE in late March, averaging 0.50" of SWE loss per day, still the lowest melt rate, from the earliest date of peak SWE at that site since 2006.

STREAM FLOWS



WY 2012 [Rio Grande River near Del Norte Stream Gauge] data for a 1,320 sq. mi. drainage area in the upper Rio Grande River watershed, above 7,980'.



WY 2012 [USGS San Juan River at Pagosa Springs Stream Gauge] data for a 281 sq. mi. drainage area in the upper San Juan River watershed, above 7,048'.

Both the above San Juan and Rio Grande River hydrographs present an early and erratic ascending limb of snowmelt runoff, with very similar numbers and timing of surges, followed by rapid descending limbs. Unseasonably warm and dry weather combined with gradually increasing reductions in snow albedo by dust in March and April produced streamflows surging to several times average discharge levels in late March, April and early May, and retreating to average flow levels between surges. Peak flow on the San Juan occurred over a month earlier than the median date whereas the Rio Grande saw nearly identical peaks bracketing a near-normal date of peak flow. That decline in flows between the two peaks on the Rio Grande may be explained by an upslope precipitation event originating in eastern Colorado delivering over an inch of precipitation as far west as Wolf Creek Summit, restoring a higher snow albedo to at least the eastern portion of the remaining snowpack in that watershed. By late May, steep declines in discharge had begun in both watersheds and resulted in flows on July 1st that are not normally seen until September.

Given the very dry spring and below-average snowpacks throughout the San Juan Mountains, below average snowmelt runoff yields in both watersheds are unsurprising. However, both the Rio Grande and San Juan river hydrographs document substantial advances in the timing of WY 2012 runoff, with the center of their respective runoff masses occurring several weeks earlier than normal. In addition to the very warm temperatures associated with prolonged periods of dry and sunny weather, dust-on-snow was also factor in this early and highly erratic runoff, hastening the “ripening” of the snowpack in March, to isothermal, and then absorbing and adding additional solar energy to the snowmelt energy budget throughout the remainder of the snowmelt season.

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