A PROPOSAL FOR A CHANGE IN WINTER SNOWPACK SUSPENSION CRITERIA USED IN THE CONDUCT OF CLOUD SEEDING PROGRAMS IN UTAH

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ABSTRACT

Cloud seeding has long been recognized as a method of precipitation augmentation. In any given year, natural precipitation may range from exceptionally low to record highs. Clearly augmentation at low and average accumulations produces substantial water supply benefits and is the primary purpose for cloud seeding – to increase water supply. However, there needs to be clear criteria by which, in high accumulation years, cloud seeding is to be suspended due to the potential for snowmelt flooding. Years that have high snowpacks also have the highest potential for longer term, sustained high streamflow and flooding, years with lower snowpacks can and do produce flood events but normally require more extraordinary climatological phenomena to produce flooding and thus lower overall potential. As there are many and sundry causes for flooding and to be clear, the flood potential to be mitigated by snowpack cloud seeding suspension is specifically springtime snowmelt flooding/runoff. Other suspension criteria are used in the conduct of the Utah cloud seeding programs (e.g. no seeding during storms with high freezing levels that could produce winter flood events). Various other flooding mechanisms such as rain on frozen soil, urban flooding from impervious surfaces, flooding resulting from channel blockages, etc. would not be impacted by or mitigated by snowpack suspension criteria.

To address the snowmelt flooding issue, streamflow points were selected that were either unimpaired or minimized upstream management. The USDA Natural Resources Conservation Service SNOTEL stations were generally selected based on high elevation and geographic location relevant to the watershed being investigated. An attempt to correlate Snow Water Equivalent (SWE) index values to observed historical flood events was largely unsuccessful. The 95th percentile or approximately the 20-year recurrence interval was used for the index suspension criteria because it assures a robust water supply for the water year and yet is low enough to reduce flood potential as many municipalities utilize the 100-year recurrence for storm water design. (KEYWORDS: cloud seeding, SNOTEL, water supply, Utah, suspension criteria)

INTRODUCTION

Cloud seeding has been conducted to impact numerous mountain barriers in Utah for many years to augment winter snowpack and subsequent streamflow. Some programs were conducted in the early 1950's then others began in the 1970's, 1980's and early 2000's. These latter programs have been conducted by North American Weather Consultants (NAWC) headquartered in Sandy, Utah. Ground-based silver iodide seeding generators are utilized to seed some naturally occurring winter some or portions of those storms. The goal is to seed storms or storm periods that are naturally inefficient in producing precipitation. Augmented precipitation typically falls as snow in the targeted mountain barriers which can lead to increased streamflow during the spring and summer months. Irrigated agricultural interests are one of the primary beneficiaries of the augmented streamflow. Various evaluations of the effectiveness of the cloud seeding programs have indicated average seasonal increases in precipitation from 3% to 17%. Griffith et al. (2009) provides an overview of the Utah cloud seeding programs including the means used to obtain estimates of the effectiveness of seeding. The Utah Division of Water Resources has conducted studies to estimate the resulting increases in streamflow based upon NAWC estimates of increases in precipitation. The most recent study (Hasenyager et al., 2012) estimated an average annual increase from the four major cloud seeding target areas of 182,000 acre-feet with an estimated cost of $2.27/acre-foot.

The genesis of snowpack suspension criteria was unclear but the values were: 200% of average on January 1, 180% on February 1, 160% on March 1 and 150% on April 1. These values would change as averages were updated every 10 years. Additional changes occurred as SWE is now represented as percent of median instead of percent of average. Given the changing nature of the current index as well as the ambiguity in which it was developed, a more thoroughly documented methodology was desired.

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Through various meetings between NRCS Snow Survey, Utah State Division of Water Resources and North American Weather Consultants it was determined that the characteristics of a suspension criteria would have the following:

1. Generated from first of month (January-April) NRCS SNOTEL SWE data that represents a fixed SWE value instead of a percentage.

2. This index would be set at a SWE level that assures an above average water year.

3. Set at such a level that municipalities could be expected to reasonably deal with potential streamflow.

4. Could deal with the variability in the amount and timing of precipitation over the winter accumulation months such that seeding activities might be suspended and then reactivated based on observed conditions.

5. Have additional mitigating criteria such as reservoir capacity to store above average expected runoff based on streamflow forecasts, expected future climatic conditions and short-term weather forecasts.

Based on these criteria, a SWE index was created from observed SNOTEL data for each basin of interest across the state set at the 95^{th} percentile. This is roughly a one-in-twenty-year SWE recurrence interval and does not imply a corresponding streamflow recurrence interval. At this level, a robust water supply is assured with the potential for flood flows diminished.

METHODS

Data used: NRCS SNOTEL, first of month SWE data, USGS daily peak and instantaneous peak flow data. Streamflow data sites were selected to include as many as possible that have a National Weather Service defined flood stage and corresponding flow rates and to have the least impairments upstream such that natural flow data are available. Stations were also selected to represent most major basins across the state.

The first step was to see if above normal SWE in January was predictive of above average SWE in April. If not, then there is little evidence that suspension as early as January could be justified. In figure 1, January 1 SWE was compared to SWE on April 1 to see if large April 1 SWE years were predictable as early as January. The results indicate that in many areas of the state, particularly northern Utah, Januaries that have top 10 snowpacks result in April 1 snowpacks that are also in the top 10 80% of the time. The Duchesne basin comes in at 60%. Some areas like the Wasatch Plateau and the upper Sevier are not as robust, falling to a 50/50 probability but oddly enough, just to the south and west, the Beaver and Coal Creek are higher at 70%. Overall, the results are strong enough to say that a discontinuation value as early as January could be considered and that the climatic conditions producing large January Snowpacks are likely to continue long enough to produce large April 1 snowpacks in most areas of Utah.

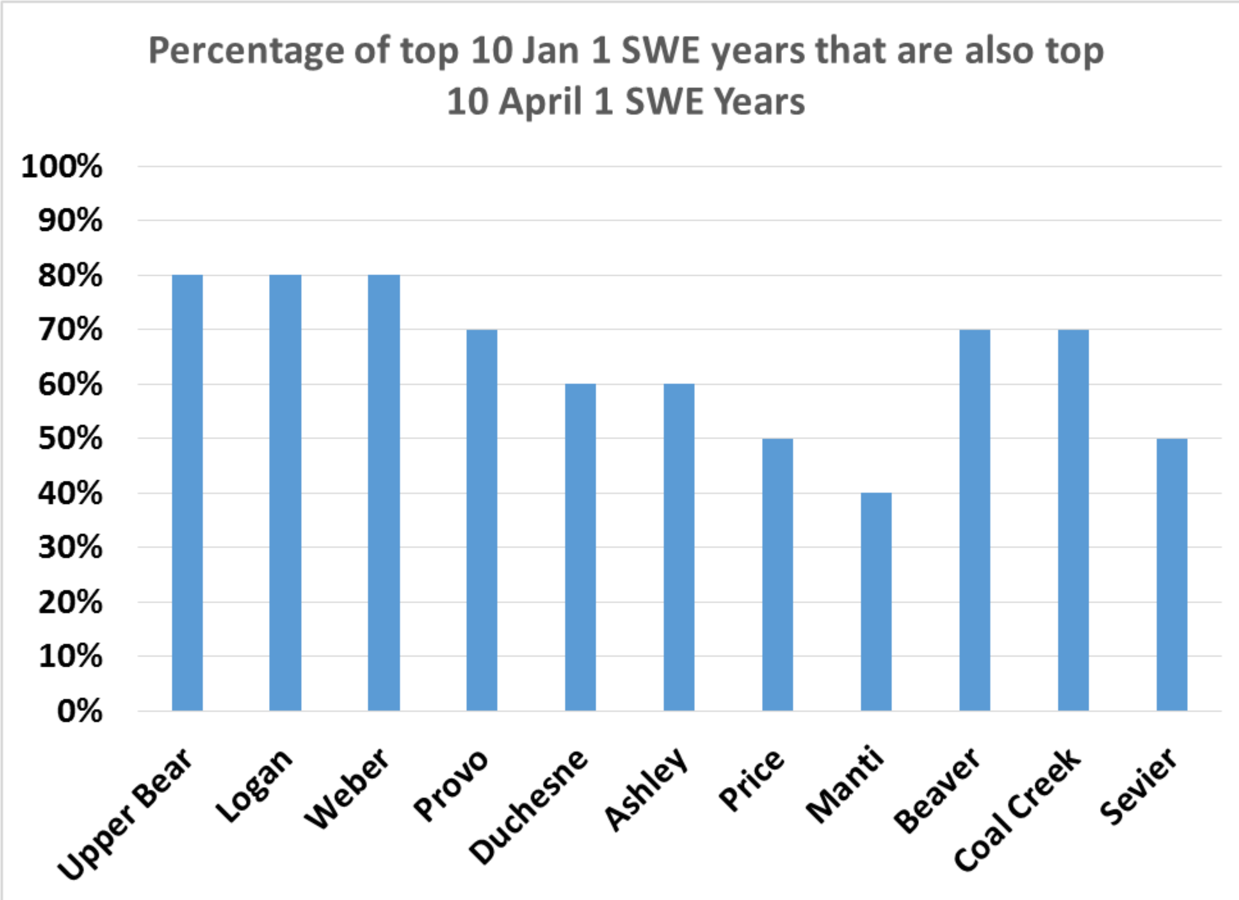

Figure 1. The percentage of top ten January 1 SWE years that result in top ten April 1 SWE years.

There are many possible ways of determining potential snowpack cessation criteria for cloud seeding including an average of the top 10% of SWE years, a probability distribution approach with selection of some recurrence interval, a basin percent of normal, tying observed floods to specific SWE levels or a set percentile. Most require some arbitrary selection such as a recurrence interval. In establishing such a criterion, it was determined that the purpose of cloud seeding was relevant – to augment water supply. As such, SWE levels sufficient to produce adequate water supply is a factor. Keeping it simple and practical is important. The 95th percentile set by the second highest observed SWE level in an approximately 40-year record is adequate to fill the role of water supply augmentation while at the same time reducing, not eliminating, flood potential. The 95th percentile is used to set the numerical SWE value that will be used as suspension criteria, a fixed value that would not change like utilizing a 30-year basin percent of average or median would at these are updated every ten years. The 95th percentile year SWE event does not imply a corresponding 95th percentile flood event. However, set much lower than this and cloud seeding water supply augmentation would be routinely suspended in years that have little flood potential. In contrast, municipalities use a 1-in-100-year event to design storm water facilities. The 95th percentile suspension criteria is far more conservative than that.

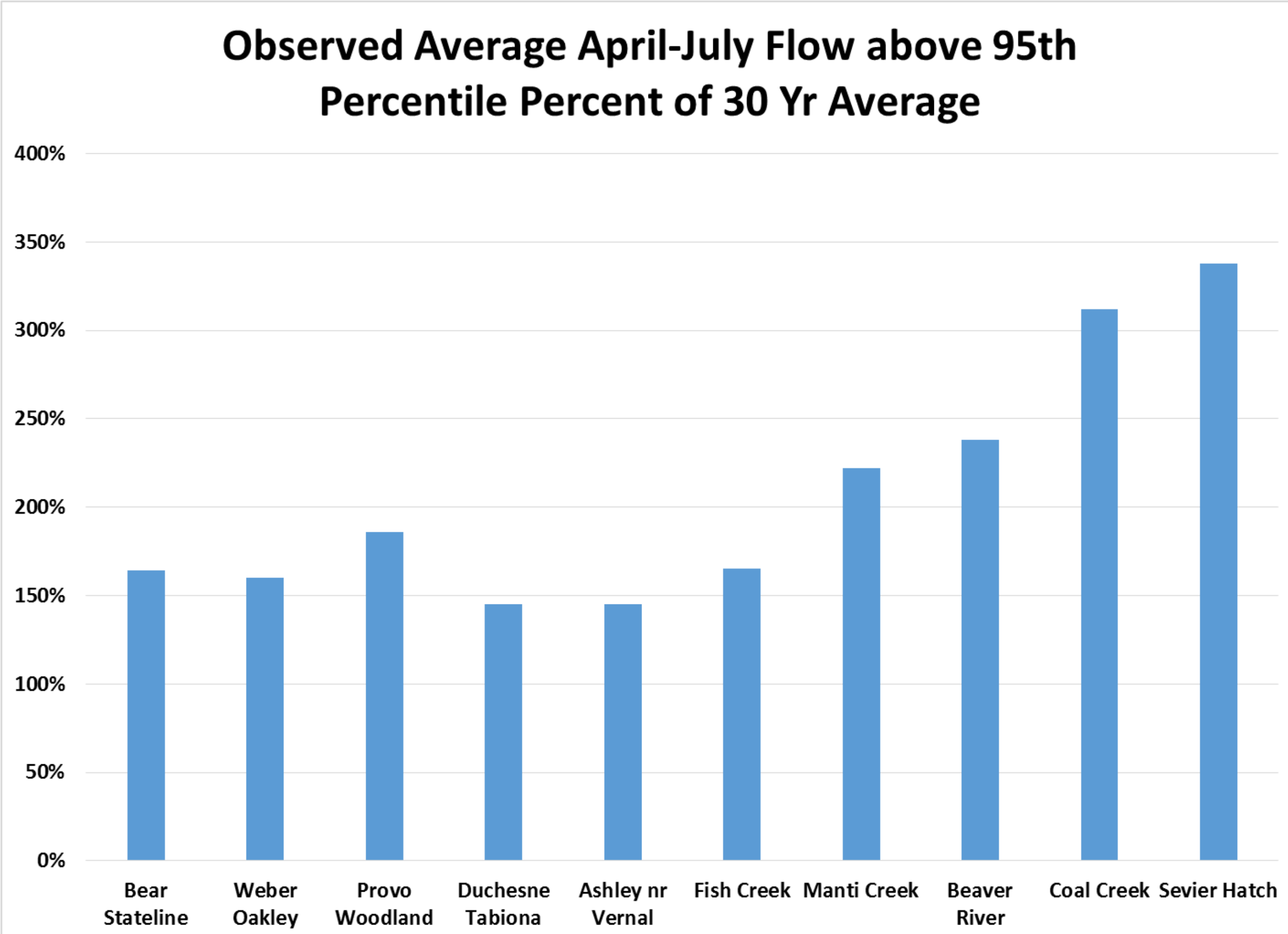

Figure 2. Observed average April-July streamflow from snowpacks above the 95th percentile

Figure 2 shows the average amount of April-July streamflow produced by snowpacks at or above the 95th percentile. For the higher elevation rivers and streams in northern Utah expected streamflows from this level of snow is between 150% and 180% of average. For the smaller rivers in central and southern Utah the range is between 160% and 350% of average. At these streamflow levels, each basin is assured a robust water supply.

A SWE index was created from the first of the month SWE values, from two high elevation stations, or one high and one mid elevation station depending on the number of stations available on the watershed. Daily snowpack suspension values consist of a straight-line interpolation between first of month values. This ties a fixed SWE value to known April-July snowmelt at a level to insure an above average water supply. Current methods utilize a basin wide percent of average methodology. The percent of average method is problematic in that the base changes every 10 years to reflect current normals. Also, in recent years, snowpack has been characterized as percent of median instead of percent of average which requires additional computation and confusion on exactly what metric should be used. The reason for high elevation stations is that snowmelt flooding and peak flows typically occur from May to early June when many of the low elevation stations have melted out and some of the mid elevation stations have also melted out. Annual peak flows come from those higher elevations on the watershed, later in the season, after which hydrograph recession normally occurs. A combination of multiple stations was originally tested but did not provide different or better results than a simple two station combination. For each month, January through April, the first of month SWE for these stations was combined and then ranked highest to lowest for the period of SNOTEL record, typically 1979-82 to 2017. The SNOTEL time frame was selected to have consistent snow data, flood flow criteria from the NWS and a most recent evaluation of known flood damages. So, for many watersheds there is between 36 to 38 observations. The top 5 years were compared to the top 5 April-July flow years. Typical results were 2 to 4 of the top snow pack years would be represented by the corresponding top April-July total flow years. Nearly all were represented in the top ten years.

An attempt was made to incorporate observed flood occurrences into the suspension criteria. This was done by taking all observed flows that exceed the National Weather Service flood stage for all streamflow sites with such criteria. The thought being that the suspension criteria could be set to the lowest observed SWE index value with an observed flood occurrence. Both instantaneous and daily average peak flows were considered. There are more observed exceedances with instantaneous peak flows than with average daily peak flows. If this was done, then suspension criteria for the Logan River would be about the 50th percentile and the 15th percentile on Coal Creek, clearly far too low to accomplish the goal of water supply augmentation.

Table 1. Monthly SWE indices above which cloud seeding would be suspended (inches)

	January	**February**	**March**	**April**	
Bear River Stateline	**32**	**41**	**58**	**63**	**Trial Lake+Hayden Fork**
Logan at Logan	**48**	**66**	**84**	**96**	**Tony Grove+Franklin Basin**
Weber at Oakley	**38**	**47**	**68**	**76**	**Trial Lake+Chalk 1**
Provo Woodland	**31**	**41**	**57**	**59**	**Trial Lake+Beaver Divide**
Fish Creek/Price	**31**	**43**	**52**	**58**	**Mammoth Cottonwood+Clear Creek 1**
Manti/San Pitch	**22**	**37**	**45**	**56**	**Buck Flat+Pickle Keg Spring**
Beaver River	**27**	**33**	**41**	**48**	**Big Flat+Merchant Valley**
Coal Creek	**44**	**46**	**71**	**77**	**Midway Valley+Webster Flat**
Sevier Hatch	**39**	**40**	**59**	**69**	**Midway Valley+Farnsworth Lake**
Duchesne Tabiona	**24**	**36**	**42**	**48**	**Brown Duck+Lakefork 1**
Ashley/Big Brush Creek	**18**	**23**	**28**	**38**	**Trout Creek+Kings Cabin**

Table 1 shows for each basin the monthly SWE index above which value cloud seeding will be suspended absent mitigating factors discussed later. It also shows the SNOTEL stations used for each watershed/area index. The first of each months SWE value at the respective sites are summed to create the index. A straight-line interpolation between the first of the month values creates a daily index.

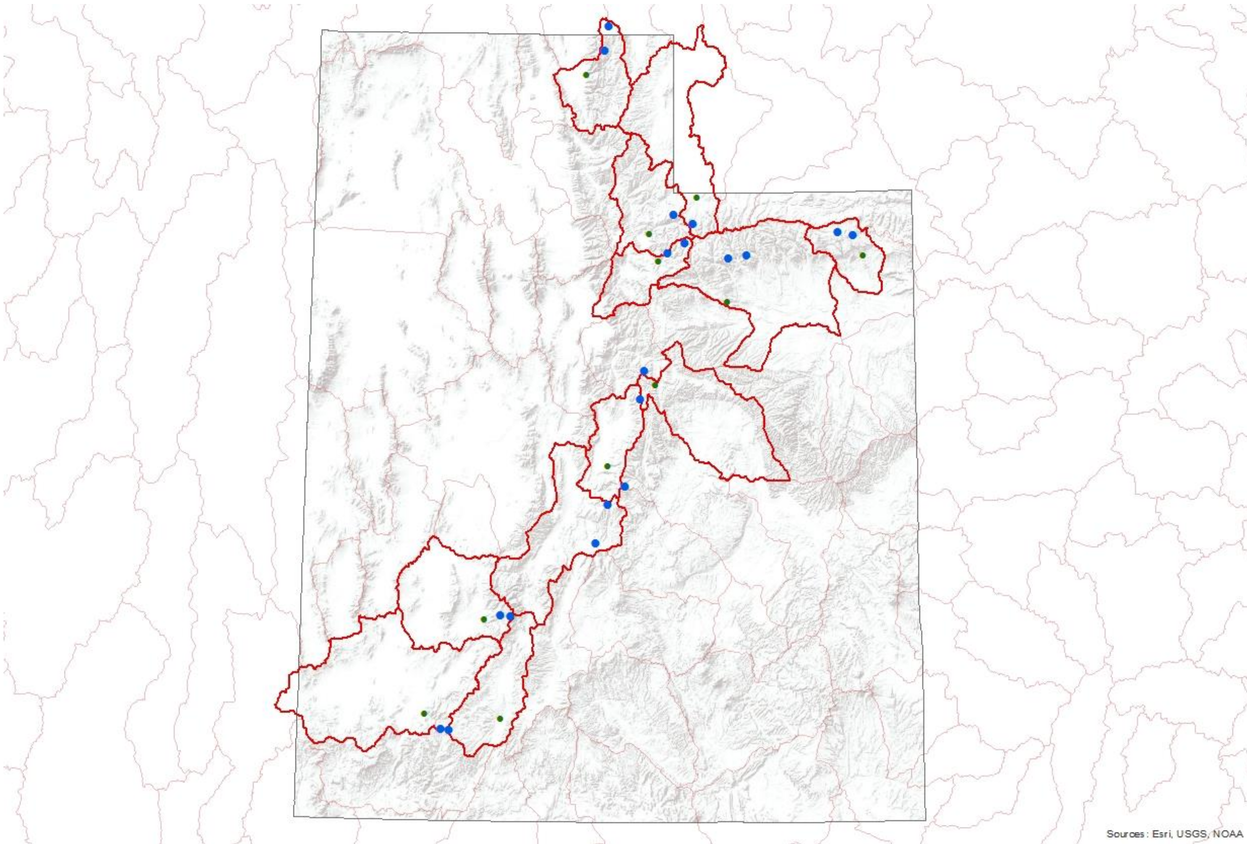

Figure 3. Watersheds and SNOTEL station locations

Figure three shows the location of each index SNOTEL station used and the various watersheds selected within the study area. As noted, a few sites are duplicated.

DISCUSSION

There will always be some level of risk involved due to the uncertain nature and unpredictability of future precipitation and other climate variables that influence flooding. Cloud seeding suspension criteria should balance the competing needs to maximize water supply benefits while minimizing flooding risk. The problem is one of using a climatological variable (some function of snowpack) to quantify the risk of flooding, of which snowpack magnitude is a function but not the only one, and in some cases, not the most important one. The fact that there is a substantial or even a record high snowpack on a given watershed does not ensure flooding will occur. The water year of 2011 saw massive snowpacks and the last flood watch for the Weber River near Oakley was issued in late July with very minimal actual flood damages. Water year 2017 was another year with exceptionally high snowpacks which failed to produce consistent high peak flows over wide geographic areas of the state. Peak flows were high but not exceptional and damages minimal. The National Weather Service peak flow forecast for the Logan River was 2100 cubic feet per second (cfs) and the observed came in at 1300 cfs, illustrating the difficulty of projecting peak flows at any time of the season unless you are within a week or 10 days of the event. In fact, peak flow data indicate that some high snowpacks don't produce commensurate high flows and vice versa – some lower snowpacks can produce high peak flows.

The definition of what constitutes a flood is also a variable that can be vague. The National Weather Service, the agency that sets flood stage defines it as that level at which damage to structures begins. The data upon which to determine a flood could be an instantaneous peak flow or a daily average flow. Daily average flow is available from most gaged USGS stations whereas instantaneous peak flow is less available and with a shorter duration record. Peak flow data are much higher than the daily average and tend to have short term impacts on flood conditions. They can also be caused by various channel conditions such as an obstruction and release or an odd combination of climate circumstances. For example, the highest instantaneous peak flows for the Provo River at

Woodland are in 1986 and 2010. The June 7, 1986 flow was the highest at 6040 cfs, well above the flood flow of 3096 cfs that was due to a dam break at Trial Lake. The other instantaneous peak flow above that 3096 level was on June 6, 2010 at 3230 cfs. This peak flow was generated from an April 1 snowpack across the Provo River watershed of 75% of average – a condition in which additional snowpack would be welcome. On the day of the peak flow, June 6th, of 17 monitoring stations across the basin, only 4 had any snow at all – 13 had already melted out. Only 2 sites, (Trial Lake and Snowbird) above 9500 feet in elevation had substantial snow to melt, and due to climate circumstances, both were well above median for that day – 175%. Trial Lake at elevation 9992 feet, the only site above the stream gage on the Provo at Woodland, had 6.9 inches of SWE on that day – hardly a great concern. There was a small precipitation event on the 4th of ½ an inch. However, the flood flow was exceeded for one day by the instantaneous peak, the daily average did not exceed flood stage. This event was a good example of how odd climate circumstances can produce exceptional short-term results. Daily average flows are longer term, sustained flows that have the potential to have more widespread impacts. As communities grow, they can become more or less susceptible to flood risk depending on what kind and where structures are built and what prevention/mitigation is accomplished. The flood stage at both the Logan River at Logan and the Weber River at Oakley have both been increased due to flood mitigation efforts. Another example, the flood damages of 1983 are widely recognized but many of the streamflows of 1984 and 1986 were higher than those that caused flooding in 1983 but did not 'flood' in those subsequent years because of prevention/mitigation efforts.

Yet another complication in this issue is the ability to manage, store or divert streamflow to prevent flooding. For example, 2017 on the Bear River – exceptionally high snowpacks created exceptionally high runoff, but over 750,000 acre-feet of water was able to be diverted and stored in Bear Lake, and without that diversion there could have been flooding issues downstream. In the record snowpack year of 2005 in southern Utah, Cedar City was able to split Coal Creek through canals and ditches to minimize water in any given channel thus avoiding/mitigating much of the potential flood damage. Many watersheds in Utah have some capacity to manage water prior to vulnerable communities. These issues noted, still the best indicator of snowmelt flood potential and associated problems is the quantity of snowpack. The period of January through April was used because to suspend cloud seeding in November or December is simply too early in the season and snowpacks too small compared to April 1 values given the huge monthly variability in precipitation throughout the winter.

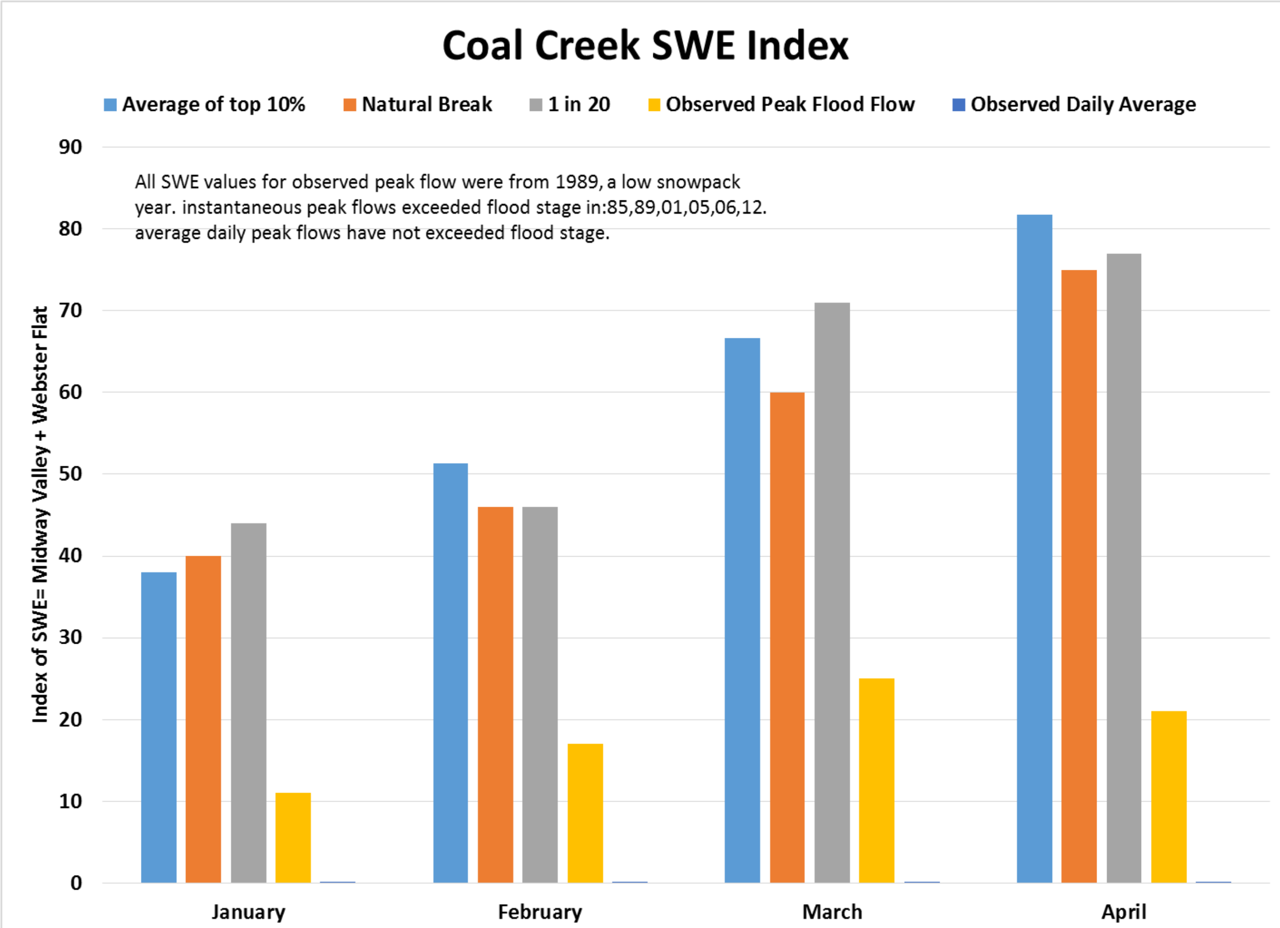

Figure 3. Coal Creek SWE Index

The Coal Creek SWE index is an example of the difficulties encountered in utilizing the observed instantaneous peak flow to determine a suspension criteria. Instantaneous peak flows exceeded the NWS flood criteria in 1985, 1989, 2001, 2005, 2006 and 2012 whereas the average daily peak flow has not exceeded the flood criteria. Moreover, 1989 was the year in which the index was the lowest for all months which is not normally the case in other locations. The April 1 snowpack of 1989 for this region was 59% of median, hardly a flooding concern. The index stations, Midway Valley and Webster Flat were at 77% and 30% of median respectively. Setting a suspension criterion at this level would place it in the 16th percentile, eliminating over 80% of all years from seeding opportunities.

The average of the top 10%, or in this case, the top 4 SWE years also has some limitations due to extreme years. Coal Creek is also an example of this. The average SWE index for April 1 is much higher that either the natural break or the 1 in 20 recurrence interval. The reason for this is there is one year, 2005 where the index is 100 inches and the second highest year, 1983 is 78 inches which skews the average value upwards. The next highest values in 1993 and 2011 are both in the 75-inch range. The 95th percentile interval is a more conservative value.

Other criteria may be used in addition to the 95th percentile SWE value to subjectively modify a suspension decision.

1. The first and foremost is reservoir capacity. If there is sufficient empty space in reservoirs such that forecast water volumes can be effectively managed to moderate peak flows, suspension might be delayed.
2. If a storm has exceeded the daily SWE suspension criteria and there are no storms forecast in the next 7 to 10 days, suspension might be delayed.

3. If the long-term climate outlook forecasts drier and warmer than normal conditions, suspension might be delayed.

The following table is a comparison of the proposed 95th percentile SWE values in inches to the current percent of average methodology. The values compared are the proposed index value and the corresponding inches of SWE that the index would have using the same stations under the current percent of average method.

Table 2. A comparison of the 95th percentile and the older percent of average suspension criteria.

	January 95th Percentile	200% of Average	February 95th Percentile	February 180% of Average	March 95th Percentile	March 160% of Average	April 95th Percentile	April 150% of Average
Bear River Stateline	32	32.2	41	44.1	58	54.1	63	62.9
Logan at Logan	48	48.8	66	73.1	84	85.4	96	101.9
Weber at Oakley	38	39.8	47	54.0	68	64.8	76	75.3
Provo Woodland	31	29	41	40.5	57	49.3	59	53.9
Fish Creek/Price	31	30.6	43	45.4	52	54.9	58	61.1
Manti/San Pitch	22	26.8	37	38.3	45	47.0	56	54.9
Beaver River	27	26	33	35.3	41	42.2	48	48.6
Coal Creek	44	30	46	42.7	71	52.6	77	61.8
Sevier Hatch	39	34	40	45.5	59	54.7	69	67.4
Duchesne Tabiona	24	26.6	36	34.2	42	40.8	48	46.4
Ashley/Big Brush Creek	18	18.4	23	22.7	28	28.0	38	33.8

In most cases, the new method of setting a fixed SWE index value based on the 95th percentile yields very similar results to the older percent of average figures. Going forward, these fixed SWE values should provide an adequate and documented basis for cloud seeding suspension. Daily values have been interpolated between first of month values such that seeding suspension can be evaluated at any time.

CONCLUSIONS

A new cloud seeding suspension process has been developed for watersheds in Utah. It fits the specified criteria of:

1. Generated from first of month (January-April) NRCS SNOTEL SWE data that represents a fixed SWE value instead of a percentage.

2. Set at a SWE level that assures an above average water year.

3. Set at such a level that municipalities could be expected to reasonably deal with potential streamflow.

4. Could deal with the variability in the amount and timing of precipitation over the winter accumulation months such that seeding activities might be suspended and then reactivated based on observed conditions.

5. Have additional mitigating criteria such as reservoir capacity to store above average expected runoff based on streamflow forecasts, expected future climatic conditions and short-term weather forecasts.

The suspension criteria of a SWE index at the 95th percentile is simple, easy to create, is a fixed number, ensures an adequate water supply and can be adjusted by mitigating circumstances. This method can also be easily adjusted for any individual watershed should conditions warrant. Attempts to include historic flood occurrences were largely unsuccessful.

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