Cloud Seeding Suspension Criteria in the State of Utah

Division of Water Resources

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Summary

"*Cloud Seeding*" or "*Weather Modification*", as defined in the cloud seeding reports of the Utah Division of Water Resources (DWRe), means all intentional acts undertaken to artificially distribute hygroscopic and ice nuclei into selected clouds to augment precipitation, mitigate hail or disperse cold fog. "Cloud seeding project" means a planned project to evaluate meteorological conditions, perform cloud seeding operations, and evaluate results. Cloud seeding in Utah typically refers to enhancement of precipitation by artificially stimulating clouds to produce more rainfall or snowfall than they would naturally. Cloud seeding is a complex process consisting of interactions between multiple atmospheric, hydrological, and human induced factors that have direct and indirect effects on snowpack, snowmelt, and snow-dominated streamflows. There are no documented reports or published journal articles that clearly guide the derivation of cloud seeding suspension criteria and the indices currently used in the State of Utah. Therefore, this document will also function as a foundation document for cloud seeding suspension activities and provide the basis for future updates and improvements to suspension criteria in the future.

This report documents proposed Snow Water Equivalent (SWE) indices-based cloud suspension criteria derived from seasonal streamflows and observed SWE values of SNOTEL stations in cloud seeding projects in the State of Utah. The objectives of this report are: (1) review and summarize the cloud seeding suspension criteria practiced in Utah and neighboring states of Utah such as Colorado, California, and Nevada; (2) evaluate the existing SWE based indices and establish a relationship between the SWE and streamflow in the cloud seeding projects; and (3) update and recommend cloud seeding suspension criteria in the project areas.

Statistical methods were adopted to establish relationships between SWE values and observed streamflows (here defined as critical flow). The critical flows represent the 95th percentile cumulative volume of the annual seasonal streamflow (April to July). The data used to calculate the seasonal cumulative volume for each of the basins were extracted from the USGS website (mostly daily flow from 1979 to 2017)The SNOTEL stations considered in this study are located within the catchment of each river basin, have long historical observational data records available, and have been continuously updated by the NRCS. The results of the SWE indices-based criteria derived from this study are similar to the existing SWE-based suspension criteria adopted in Utah. For example, currently a cloud seeding project in Utah is flagged for possible suspension if SWE values observed from one or more SNOTEL sites in a given basin exceeds 200% of the average on January 1, 180% on February 1, 160% on March 1, or 150% on April 1. The calculated average suspension criteria from this study are 230%, 197%, 183%, and 178% for January 1, February 1, March 1, and April 1, respectively. Unlike the existing practice of taking a single percentage value for the entire state, it proposes basin/project specific SWE instantaneous value for each month and

varies with the basins. The results also suggest the ranking of the SNOTEL stations to be considered during the suspension decision. Recognizing the complexity, variability, and uncertainties in the metrological variables, cloud seeding processes, and watersheds, the final suspension decision should be made after a thorough assessment of other important factors including: (1) extreme weather conditions: warning of extreme storms, avalanche danger, local flooding, or potential flash flood warnings; (2) amount of precipitation in prior seasons, soil moisture conditions in the basin, reservoir storage level, and stream flow forecasts; and (3) potential increased risks of flooding due to wild fires.

The report consists of four sections. The first section presents background information on the need of cloud seeding in general, a brief review on the cloud suspension criteria, and the cloud seeding projects in Utah. Section two discusses methods/approaches adopted to develop the suspension criteria and sources of data considered for the analysis. Section three presents results for nine river basins and project areas where cloud seeding and suspension will be implemented. Most of the data considered for the analysis are from USGS (U.S. Geological Survey), USDA (U.S. Department of Agriculture), NRCS (Natural Resources Conservation Service) and NOAA (National Weather Service National Oceanic and Atmospheric Administration). This section also presents the results of the SWE-based suspension indices with reference to the SNOTEL observations. It is noted that new Six Creeks of Salt Lake City and other potential seeding watersheds, which were not seeded prior to year 2017/2018, are not included in this report. Section four includes the summary and recommendations of the study. The SWE values indices derived from this study are consistent with existing SWE suspension-based criteria practices in the State of Utah with the main difference being variability between basins.

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1. Introduction

1.1 Background

Past decadal climate records indicate that significant parts of the western United States are experiencing ongoing snowfall deficits and drought. Observed changes in the recent weather patterns has resulted in modification of the intensity and magnitude of precipitation averages. Frequent extreme low precipitation events have resulted in major river systems receiving record low inflows. Moreover, increased total water demand due to rapid population and economic growth and the direct and indirect impact of climate variability in all aspects of water use, including municipal water supply, groundwater availability, agricultural production, industries, and ecosystems services, has resulted increased pressures in scarce water resources. Within this context, cloud seeding has been one of the well-recognized and adopted options for enhancing water supplies in the western United States and other parts of the world (Bruintjes, 1999; Breed et al., 2013; Griffith et al., 2009; Silverman, 2010).

Weather modification by human activity in order to enhance rainfall and snowfall, and suppress hail started with experimentation by Langmuir and Schaefer in 1948 (Schaefer 1949). Depending on the objectives, the weather modification types include ground-based snowpack augmentation, airplane-based snowpack augmentation, airplane-based rain augmentation, hail suppression to reduce crop and property damage, and fog suppression near airports. A seeding agent, such as microscopic-sized silver iodide particles, is used to cause condensation-forming cloud droplets that subsequently freeze or cause naturally occurring cloud droplets to freeze, forming ice crystals. These ice crystals grow and fall to the ground as snow or as rain, depending on the surface temperature. Figure 1 illustrates the processes of the ground-based cloud seeding.

Several professional scientific organizations, including the American Meteorological Society and the World Meteorological Organization, have supported the scientific credibility of cloud seeding based upon statistical evidence that if the seeding operations are properly designed and conducted, they can augment seasonal precipitation theoretically by up to 15% (DeFelice et al., 2014; Griffith et al., 2009). The effectiveness of cloud seeding depends on temperatures, available water in the atmosphere, ice nuclei properties, cloud droplets, and natural ice distributions (NRC, 2004; Reynolds, 2015). Past research has demonstrated that cloud seeding projects can help to augment water supply sources, poses no environmental or health risk, is much less expensive than other water augmentation technologies, and may have large benefit-to-cost ratios. It is noted that cloud seeding does not create clouds to seed, and it is only effective when naturally occurring ice nuclei are limited but nature is performing the other required precipitation processes.

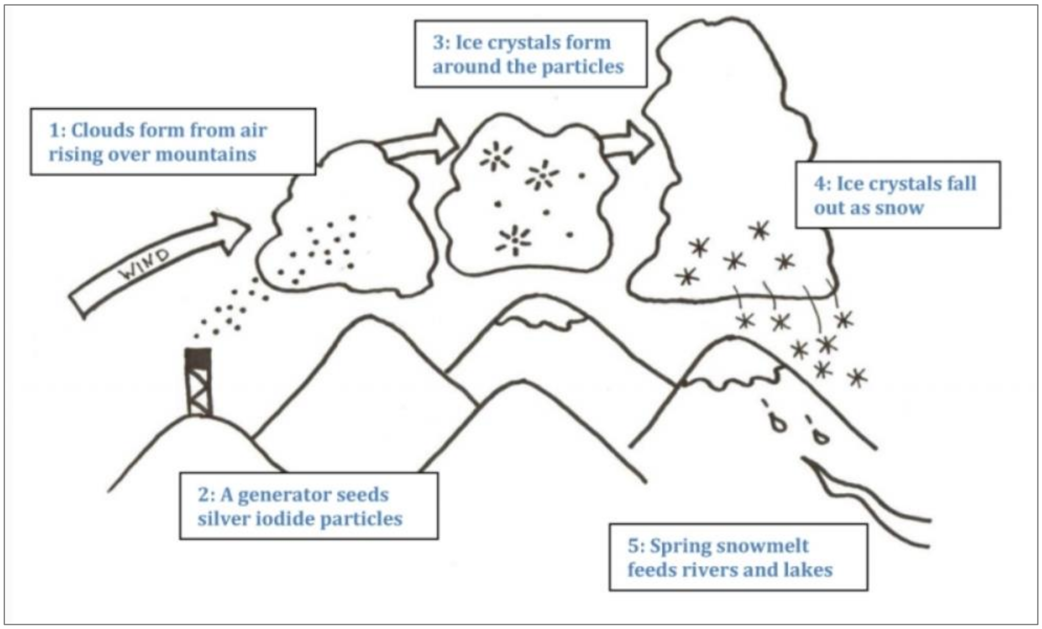


Figure 1. *Ground based winter cloud seeding processes (Source: https://climateviewer.com/2014/03/25/history-cloud-seeding-pluviculture-hurricane-hacking/).*

1.2 Cloud Seeding Program in Utah

The main purpose of the Utah cloud seeding program is to enhance precipitation and snowfall to improve water supplies within the state. Cloud seeding in Utah initially began in the early 1950s and operated for two years, and in 1973 the Utah State Legislature passed the Utah Cloud Seeding Act, which determined that additional water was to be considered part of Utah's basic water supply.

The Cloud Seeding Act of 1973 gave authority to the Utah Division of Water Resources (DWRe) to be the only entity to authorize and/or permit cloud seeding projects in Utah. Since 1976, the DWRe has provided financial assistance to run the seeding program. From 1976 to 1981, the total cost of cloud seeding was shared between the state and local sponsors, where the state funded 70% of the project costs and local sponsors covered the remaining 30%. Funding was somewhat limited until 1989 due to the economic downtown in the early 1980s and the extremely wet seasons. However, in 1991 the legislature authorized the DWRe to fund half the cost of cloud seeding projects up to $150,000 each year from its Revolving Construction Fund. In 2007, more funding was allocated to cloud seeding projects when the legislature approved an additional $150,000 from sales tax funds. This allocation authorized total cloud seeding funds of up to $300,000 annually from the state, with a cost share of 50% of total project costs. As the projects have changed over the years there have been a variety of local sponsors.

Currently there are five sponsored projects in Utah (Figure 2) that include Central and Southern Utah project areas, Northern Utah project areas, West Uinta's project area, High Uinta's project area, and the Emery propane project area (Table 1).

Table 1. *Summary of cloud seeding project areas*

Project Area	Number of Cloud Seeding Generators 2017-2018 Season	Seeded Seasons
Central/Southern Utah	65	41
Tooele County	11	34
East Box Elder/Cache County	21	28
West Box Elder	10	26
Western Uinta	13	23
High Uinta	24	29

The Central and Southern Utah project, comprising the Central/Southern Utah and Tooele County areas, is sponsored locally by the Utah Water Resources Development Corporation. The Northern Utah project, comprising the West Box Elder and the East Box Elder/Cache County areas, is sponsored locally by Bear River Water Conservancy District and Cache County. The West Uinta project is sponsored by Weber Basin Water Conservancy District, Provo River Water Users Association, and Central Utah Water Conservancy District. The High Uinta project is sponsored by Central Utah Water Conservancy District, Duchesne County Water Conservancy District, and Uintah Water Conservancy District. Extended seeding periods in November and April are funded by the Lower Colorado River Basin States in an effort to augment water supply to the Colorado River, High Uinta, Central and Southern Projects areas. The Emery propane project is sponsored by the Emery Water Conservancy District. The contractor for all of the silver iodide projects is North American Weather Consultants located in Sandy, Utah.

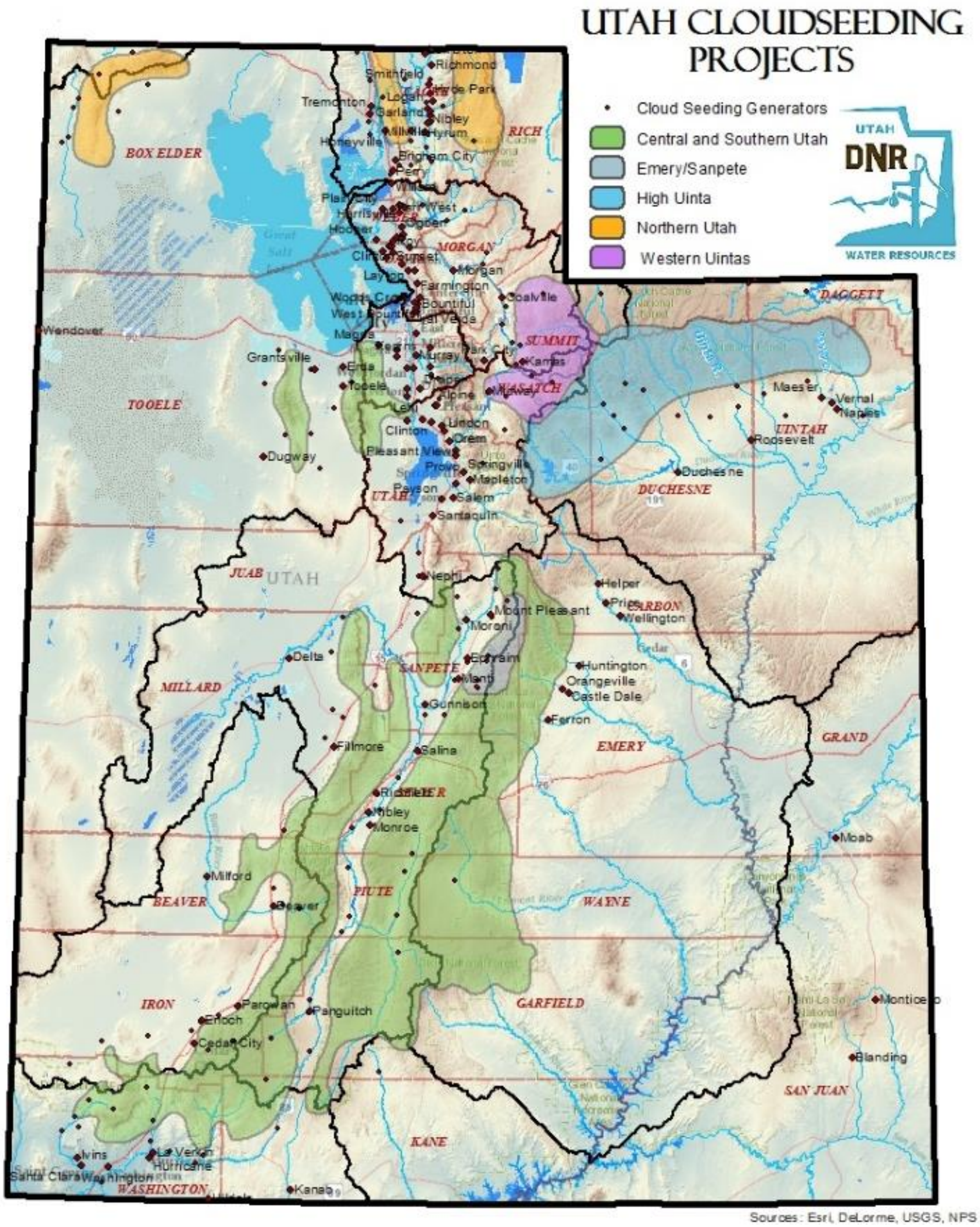


Figure 2. *Major cloud seeding project areas in the State of Utah.*

All of the cloud seeding programs in Utah are ground-based winter cloud seeding and operate during the December to March period, with the exception of the High Uinta and Central and Southern Utah projects, which run longer. Starting in 2007, the Lower Colorado River Basin States have funded an extension of the cloud seeding period in the High Uinta project (November 1-30) and the Central and Southern Utah project (November 1-15 and March 16 -April 15).

The operational winter cloud seeding programs in Utah rely upon the release of Silver Iodide nuclei from strategically placed, manually operated ground generators located in valley or foothill locations (see Photos 1). North American Weather Consultants Inc. is responsible to install and operate the ground-based generators in the project areas. The current seeding solution contains 2% silver iodide complexed with sodium iodide and paradichloro-benzene dissolved in acetone that is burned in a propane flame (Griffith et al., 2009). The most recent report (Nay et al., 2018) estimated an average annual increase from the four major cloud seeding target areas of nearly182,000 acre-feet (ac.ft.), with an average per acre-foot cost of $2.27 (i.e., in a range of $1.62 to $3.12 per acre-foot).

Photos 1: *Ground based cloud seeding generators installed and operated in the Utah's cloud seeding projects by North American Weather Consultants*

1.3 Cloud Suspension Criteria in Utah and Neighboring States

Cloud seeding suspension criteria are required to prevent seeding when heavy snowpack or other potentially hazardous conditions are present. In Utah, cloud seeding programs are suspended upon the evaluation of percentage of mean SWE values, heavy rain on snow events, NWS flash flood warnings, existing reservoir levels, and soil moisture contents. The current monthly SWE threshold values considered for January 1, February 1, March 1, and April 1 are 200%, 180%, 160% and 150% of the average values, respectively. This SWE-based main criterion is supplemented by the assessment of other multiple hydrological and metrological data such as reservoir levels, soil moisture levels, amount of precipitation in prior seasons, wild fire areas, and stream flow forecasts, before making a final suspension decision. However, the suspensions for severe weather are done regardless of current SWE values. The current SWE threshold values practiced in the state are simple to apply and verify, however, the state currently cannot determine how these threshold values of SWE were derived and how those single SWE index can be applicable for all the watersheds.

Neighboring states of Utah have also used SWE values as one of the main suspension criteria. For example, California has cloud seeding suspension criteria that stop cloud seeding at any time there is a flood threat, heavy snowpack, or other potentially hazardous conditions (Hunter, 2007). Weather modification projects employ a combined interdisciplinary team of meteorologists to monitor the current and projected weather conditions, and water management personnel to monitor streamflow and reservoir storage. The combined interdisciplinary data concerning flood potential are evaluated and conditions are compared against suspension criteria in advance of any potential flood risks.

In California, a recent design study for a winter cloud seeding program in the Lake Lopez and Salinas Reservoir drainages (Griffith et al., 2017) proposed three suspension criteria: (1) whenever the National Weather Service (NWS) issues a severe storm, precipitation, flood or flash flood warning that affects any part of the project area, the project meteorologist shall suspend operations which may affect that part; operations will be suspended at least for the period that the warning is in effect; (2) in the event that unforeseen conditions develop during storm events that in the Project Meteorologist or District/Agency personnel's best judgment have the potential to cause flooding or other adverse conditions anywhere within the project area, operations shall be suspended for any part, or all of the project area; and (3) if either of the target reservoirs fills during the winter season, operations shall be suspended unless storage drops below the capacity of the reservoir later during the winter season.

The State of Colorado also suggests three criteria to suspend cloud seeding (Wilsonwater, 2015): (1) *Snow Water Equivalent Thresholds*: weather modification operations must be suspended at any time the SWE exceeds 175% of average on December 1st, 175% on January 1st, 160% on February 1st, 150% on March 1st, or 140% on April 1st. The Executive Director of the Department of Natural Resources or his or her designee will determine where and how SWE's are to be measured, including at selected SNOTEL sites; (2) *Avalanche Hazard Levels:* weather modification operations may be suspended due to high avalanche hazard levels for highway corridors as determined by the Colorado Avalanche Information Center; and (3) *National Weather Service Hazardous Weather Statements*: weather modification operations must be suspended whenever one of the following is issued that impacts any part of the target area: an urban or small stream flood advisory; a blizzard warning; a flash flood warning; or a severe thunderstorm warning. Operations may resume after these statements expire.

The State of Nevada has three criteria (DRI, 2006) for cloud seeding suspension as well: (1) weather modification operations must be suspended at any time the SWE exceeds 175% of average on December 1st, 150% on January 1st, 150% on February 1st, 150% on March 1st, or 140% on April 1st; intermediate limits shall be derived by linear interpolation between the percentages given above; (2) suspension will occur at times of extreme weather such as when an extreme avalanche danger exists as determined by the U.S. Forest Service, when the NWS forecasts a warm winter storm (freezing level >8000 feet) with the possibility of considerable rain at the higher elevations that might lead to local flooding, when the Project Meteorologist determines that potential flood conditions may exist in or around any of the project areas, when flash flood warnings are issued by the NWS, or when forecasts of excessive runoff are issued by the River Forecast Center; (3) suspension will occur when the wind speed is 60 knots (≈69 mi/hr) or more for over 30 minutes at the 700 mb level (~10,000 feet) and wind directions lie outside of the range between 180 and 330 degrees during ground-based seeding operations on the west side of the Sierra Nevada crest.

1.4 Selection of Cloud Suspension Criteria and Methods

There are no focused discussions about the selection and analysis of cloud suspension criteria in any published scientific journal articles. A few of the publications discuss the statistical and high-resolution modeling approach to assess the effectiveness of cloud seeding. The statistical methods are very simple and commonly used to establish the relationship of rainfall and runoff using a target and control approach (Benjamini et al., 1986; Gagin et al., 1981; Hunter, 2006). They relate the multiple predictors of stream flows in a river basin, including such predictors as precipitation, snowpack, temperature, wind speed, relative humidity, solar radiation, evapotranspiration, reservoir storage level, soil infiltration, antecedent soil moisture, slope and aspect, vegetative cover, and more. Different statistical methods, including linear regression, principal component analysis, canonical correlation analysis, neural network, and other databased analysis, have been applied in different parts of the world. Moreover, system models (hydrological models) and semi-empirical approaches are also commonly used for streamflow predictions.

The statistical methods can be applicable if the multiple predictors are available. However, analysis challenges arise if there are a large number of variables, since many of the variables may be inter-related (i.e., collinearity between the variables such as precipitation, snowpack, snow water equivalent, soil moisture contents, etc.). In several cases, reliable and continuous data are limited. It is therefore critical to select a key number of predictors suitable for local conditions that meet the objectives of the analyses.

Recent modeling practices are moving toward the development of a high-resolution cloud seeding system model. The high-resolution modeling approach considers all the parameters, including bulk microphysical parameterizations that drive for hydrological changes, wind, temperature, snow, winter orographic clouds. Based on this modeling approach, the National Center for Atmospheric Research (NCAR) developed a new cloud seeding module on the Weather Research Forecasting (WRF) model. The module uses the databases of radiometer, snow gauge, and sounding, and has been proven to perform reasonably well for most cases. It was used to simulate the effectiveness of the Idaho Power Operational Seeding Program (Tessendorf et al., 2015). However, this module demands a high level of technical knowledge on atmospheric physics, intensive data input, and huge computational resources, which are often unavailable in most state agencies.

In mountainous regions, snowpack significantly affects catchment hydrology by temporarily storing and releasing water on various time scales. The rate of snowmelt is a crucial element in runoff prediction. Snowmelt is generally modeled either by using energy balance models that quantify melt as residual in the heat balance equation, or by the temperature index models assuming an empirical relationship between air temperatures and melt rates. Therefore, snowmelt analysis requires understanding of the combination of energy balance equations consisting of temperature, solar and thermal radiation, precipitation, humidity, wind, and cloudiness components. Analysis of the snowmelt and resulting runoff also requires physical-based models and model calibration, which is beyond the scope of this study.

Moreover, the streamflow and runoff in any location is governed by the interactions of hydrologic, atmospheric, and oceanic factors. The hydrologic factors include precipitation, SWE, lagged precipitation, lagged stream flows, soil moisture contents, and more. The potential atmospheric and oceanic predictors include elevation, wind speed, air temperature, radiation, relative humidity, the Artic Oscillation (AO) index, the Pacific Decadal Oscillation (PDO) index, the Southern Oscillation Index (SOI), the North Atlantic Oscillation (NAO) index, sea surface temperatures (SST), SSTs related to El Niño-2, El Niño-3, and El Niño-4, and more. Analysis of all the major factors and their interactions, is a very resource intensive (Chang & Jung, 2010), therefore are beyond the scope of this study.

The risk of flooding has been one of the important factors considered for the cloud seeding suspension criteria. Most of the time a magnitude of flood is estimated using the IDF analysis (i.e., relationship of the intensity of rainfall (I), duration (D), and frequency (F)). The chance of flooding of different magnitudes is expressed in the concept of a recurrence interval, which is an average period for a flood that equals or exceeds a given magnitude, expressed as a period of years. Generally, flood-frequency curves express the chances of equaling or exceeding a given discharge in terms of the concept of flood frequency or probability. Often, a large, catastrophic flood has a very low frequency or probability of occurrence, whereas smaller floods occur more often. Estimating the peak flow resulting from the runoff volume generated from rainfall and/or snowmelt events and time distribution of flow is a complex undertaking; therefore, analysis of flooding probability and flood risk assessment is beyond the scope of this study. However, the risks of flooding perceived by the decision maker, based on flood forecasts and/or warnings issued by the NWS or other regional authorities, will be considered as one of the cloud seeding criteria. Therefore, a short-term winter flood forecasts are not the subject of this report.

1.5 Purpose and Scope

From the brief review, it is evident that common suspension criteria selected and practiced by the state agencies are driven by three objectives: (1) criteria are easy to implement, with the percentage of SWE values based on the SNOTEL observations as one of the criteria; (2) augmentation of the water supply sources; seeding process are continued unless heavy snowfalls and surplus reservoir storage exists; (3) avoiding risks due to natural extremity; suspension occurs if there is any possibility of direct flooding/flash flooding or avalanche when seeding or with perceived flooding in the summer.

The cloud seeding criteria, considered in Utah and other neighboring states, clearly indicate that seeding can be continued to ensure sufficient water supply level while avoiding flood risks. Earlier studies indicate that cloud seeding can augment the gross precipitation by 5% to 15% (DeFelice et al. 2014, Mason and Chaara, 2007). Given an assumed 10% SWE increase, April to July seasonal runoff increases varied from 6% to 21% (Super et al., 1993; Hunter, 2005). Considering the potential losses of precipitation from the hydrological processes such as evapotranspiration and topographical variability, it is likely that the augmented streamflow due to cloud seeding will be lower than augmented precipitation (i.e., 5% to 10%). It is evident that most of the stream flows accumulated during the winter and summer seasons in Utah are predominantly due to snowmelt. Therefore, the total accumulated seasonal streamflow volume can be a good base to derive cloud seeding suspension criteria.

The objective here is to establish a relationship of a 95th percentile of the cumulative seasonal streamflow volume in a basin to the SWE values. The 95th percentile value of the cumulative seasonal volume is defined hereafter as a "critical streamflow". Thus, the SWE indices to be considered as a suspension criterion, will be derived from the critical stream flow and historical observed SWE values. The motivation for considering the 95th percentile of the cumulative seasonal volume of the stream flows was to ensure sufficient water supply sources in a basin nearly at the level of the historical maximum. It is assumed that total water yields (precipitation to runoff) generated within the period of April 1 to July 31 will reflect most of the seasonal variabilities (early and late snowmelt) and interactions of the climatic and hydrologic factors in a season. The seasonal streamflow from a basin depends on multiple factors including rain to snow ratio, SWE, air temperature, reservoir level, groundwater, atmospheric-oceanic forcing factors, earlier seasonal streamflows, moisture contents, and more. The SWE indices derived after evaluation of the streamflow will be more representative than solely considering the SWE value.

The purpose of this report is to evaluate the existing cloud seeding suspension criteria, and recommend simple and sound cloud seeding suspension criteria in the state of Utah. As stated, the objectives of this report are: (1) review and summarize the cloud seeding suspension criteria practiced in Utah and neighboring states of Utah such as Colorado, California, and Nevada, (2) evaluate the existing SWE based indices and establish a relationship between the SWE and streamflow in the cloud seeding projects, and (3) update and recommend the cloud seeding suspension criteria in the project areas. The next section of the report presents a methodology to establish a SWE value as the spring/summer suspension criterion.

2. Methods of Analysis

2.1 Study Areas and Data

This study covers the cloud seeding project areas of the State of Utah (Figure 1). The SWE data were extracted from the NRCS (https://www.wcc.nrcs.usda.gov/snow/snow_map.html). As far as possible, the SNOTEL stations, which hold longtime and reliable data sources (mainly starting from 1979), have been considered for the analysis.

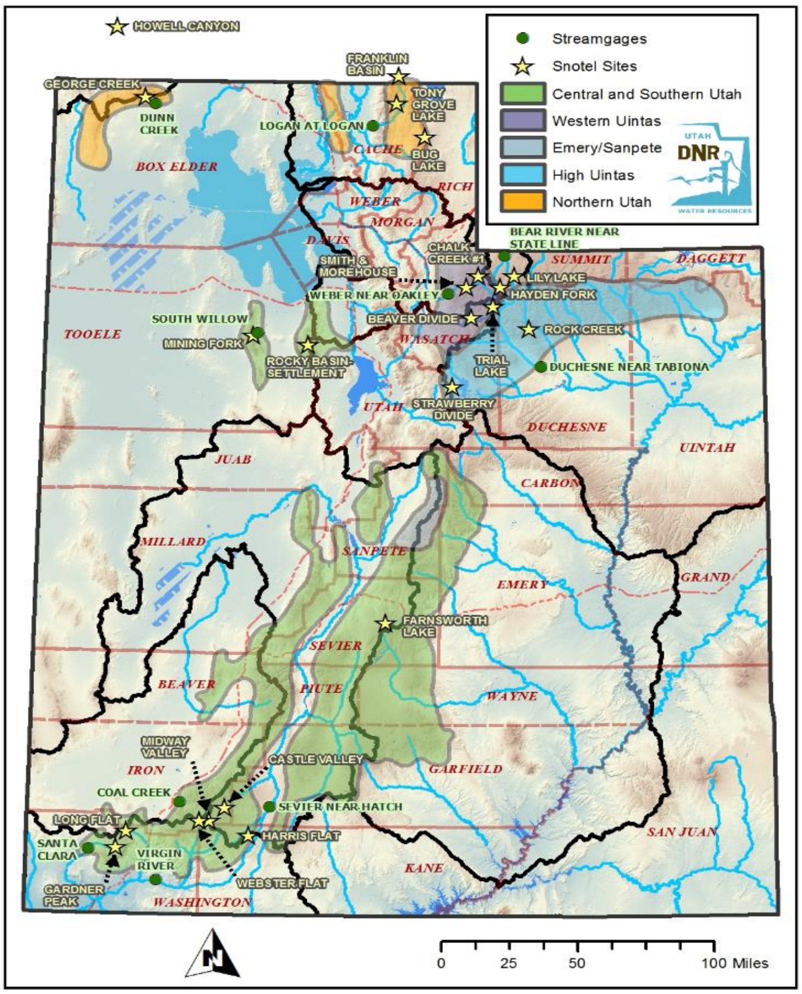


Figure 3. *SNOTEL sites and streamgage stations considered for the analysis*

Streamflow related data (either daily average or daily peak) for each of the basins were extracted from the USGS website (https://waterdata.usgs.gov/ut/nwis/rt). Streamgage stations selected for the analysis have no or negligible effects of the human interventions, and the observed flow will represent the natural flow generated from a basin of interest. Data related to flood levels and historical flood records were extracted from the NOAA website. Figure 3 presents the main SNOTEL and the streamgage sites considered in this study. It is noted that new six creeks and potential seeding watersheds, which were not seeded prior to year 2017/2018, are not included in this report.

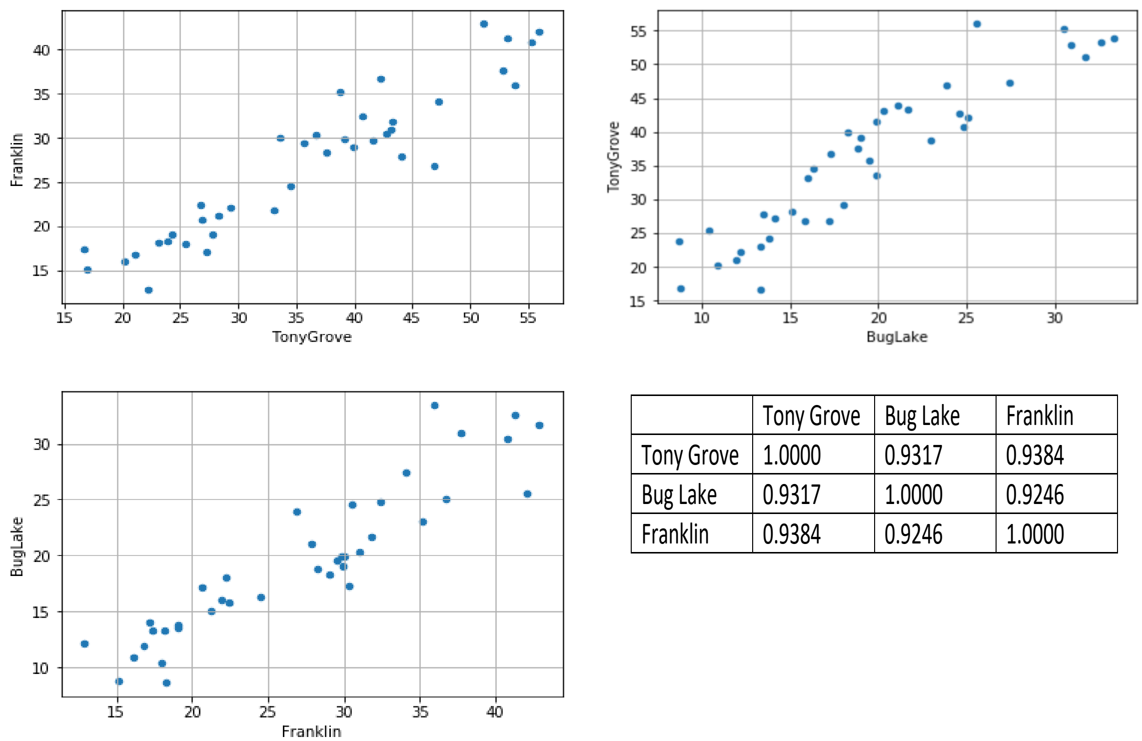
2.2 Analysis Approaches

2.2.1 Statistical Methods: Linear Regression and Stepwise Regression

The three statistical methods commonly used to establish the relationship between the predictors and predictand in hydrological and streamflow forecasting are simple and multiple linear regression (Wilby et al., 2004); principal component analysis (PCA) (Jolliffe, 1986; Haan, 2002; Manly & Alberto, 2016); and Canonical Correlation Analysis (CCA) (Glahn, 1968; Haan, 2002). As indicated, a large number of variables may be potentially used for streamflow forecasting and many of the variables may be interrelated (i.e. collinearity between the variables) (Haan, 2002; Manly & Alberto, 2016).

A multi-collinearity was checked between the SNOTEL stations where the SWE values were recorded. As presented in Figure 4, the scatter plots and co-variance matrix clearly indicate the existence of the multi-collinearity between the SNOTEL stations considered for the Logan River basin. Similar types of the relationship (>30 years if available) were observed in all SNOTEL sites.

Generally, PCA and CCA methods are mostly recommended in the case of a large number of variables that are inter-correlated. However, from the practical operational point of view, application of those techniques seems to be complicated. For example, if we apply the PCA method, PCA converts multiple input variables into the new PCAs (the new PCAs are the result of the combined data, see more discussion on PCA technique in Jolliffe and Cadima, 2016 and cited sources there). Let us assume that the PCA based index was generated using four SNOTEL observations in a basin. During the implementation, if any one or more of the observations out of the four stations is missing, the established PCAs-based index derived from the four stations cannot be readily applicable. This means it needs additional analysis at the time of implementation in case the observations are missing/not available. If we chose to apply CCA, a similar level of complexity has to be dealt. In order to overcome this type of implementation challenge, a linear regression model was developed to establish the relationship between the SWEs and streamflows. This means, streamflow will be evaluated for each of the main SNOTEL stations in a basin. However, to select the important predicator/SNOTEL a Stepwise Regression Method with forward elimination technique was considered. The Stepwise regression is a variable selection procedure for independent variables. At each step of the analysis, each independent variable is evaluated using a set of criteria to decide if the variable should be included (Ssegane et al, 2012). The coefficient of determination (R^2) and *p*-statistics, commonly used indicators, are used to rank the SNOTEL statins in a basin.



	Tony Grove	Bug Lake	Franklin
Tony Grove	1.0000	0.9317	0.9384
Bug Lake	0.9317	1.0000	0.9246
Franklin	0.9384	0.9246	1.0000

Figure 4. *Scatter plots of the SWE values between the SNOTEL stations and a table of covariance matrix between the three SNOTEL stations in the Logan basin.*

2.2.2 Statistical Relationship between the Observed SWE Values

As discussed, the main objective of the study was to establish relationship between SWE and streamflows in a basin. In this case, it was hypothesized that January to April SWE values observed in each of the SNOTEL site has a strong statistical relationship. To verify this, it was evaluated that if the observed SWE values on January 1 had a statistical relationship with SWE values on April 1 (Figure 5). Most of the river basins, except in Box Elder and Tooele project areas, have SNOTEL data available since 1979. For the Box Elder area, a SNOTEL station from Idaho (Howell Canyon) was used because of its geographical proximity to the project areas and has observations available since 1981. The Howell Canyon station supplements the George Creek SNOTEL station, which has observations available since 2011. The Tooele project areas are covered by two stations (Mining Fork and Rocky Basin), which have SWE data available since 1989 and 1982, respectively.

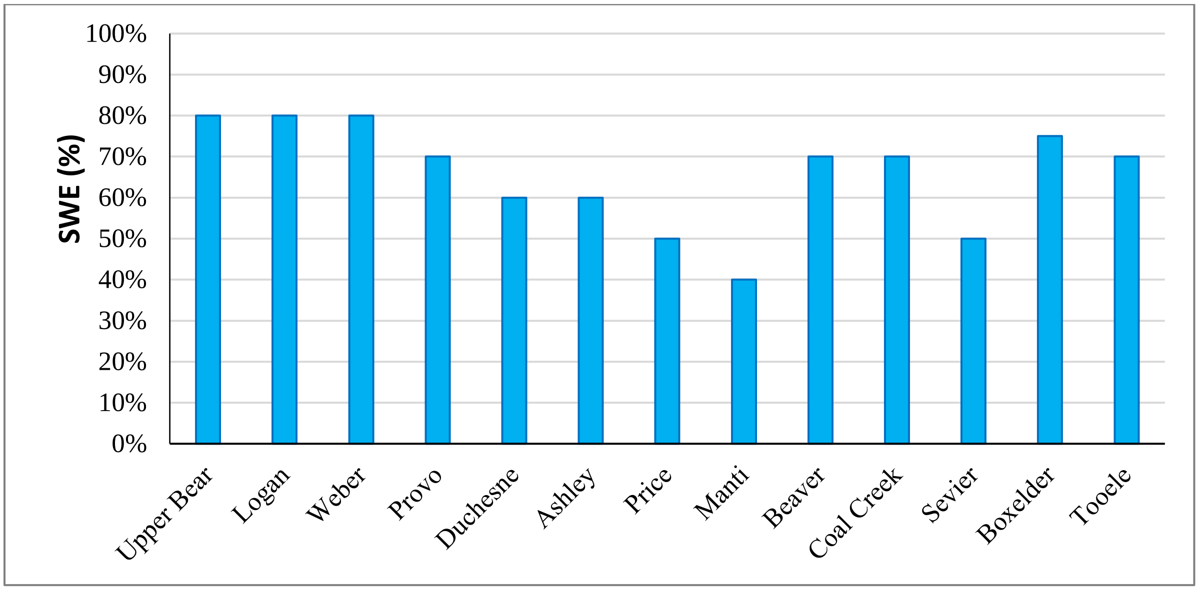


Figure 5. *The percentage of top ten January first SWE years that result in top ten April first SWE years for the project areas*

Figure 5 indicates that in many areas of Utah, particularly northern Utah, Januarys that have top ten snowpacks result in April 1 snowpacks that are also high 80% of the time. The Duchesne Basin comes in at 60%. Some areas like the Wasatch Plateau and the upper Sevier have the highest variability, falling to a 50/50 probability, but oddly enough, just to the south and west, Beaver and Coal Creek are higher at 70%. Overall, a linear correlation exists between the SWE values of January 1 and April 1. 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.

2.2.3 Application Example

This section presents an application example of the proposed method in the Logan basin. As discussed, the cumulative streamflow volume is derived by aggregating streamflow generated in a basin in the period between April 1 and July 31. The daily streamflow data used in the analysis were extracted from the USGS streamgages. Figure 6 shows the cumulative volume of the annual seasonal streamflow for 1978 to 2017 in the Logan basin (USGS station: 10109000). The blue line indicates the annual seasonal (April 1 and July 31) total cumulative volume (in ac-ft). The red line shows the 95th percentile level of the average seasonal cumulative flow of the last 40 years. The black line represents a mean annual flow in the observed periods. The red line (95th percentile of volume) will be considered here as the critical or highest level of the volume that can be targeted for a cloud seeding project. This means the SWE indices corresponding to the critical stream flows (red line) from January to April will be identified for all the project areas. It implies that if the seasonal streamflow in a basin exceeds the critical flow, then the cloud seeding project will be suspended. In this example, years 1984, 1986, 2011, and 2017 suggest the cloud seeding would have been suspended but the exact values and month will depend on the SWE values.

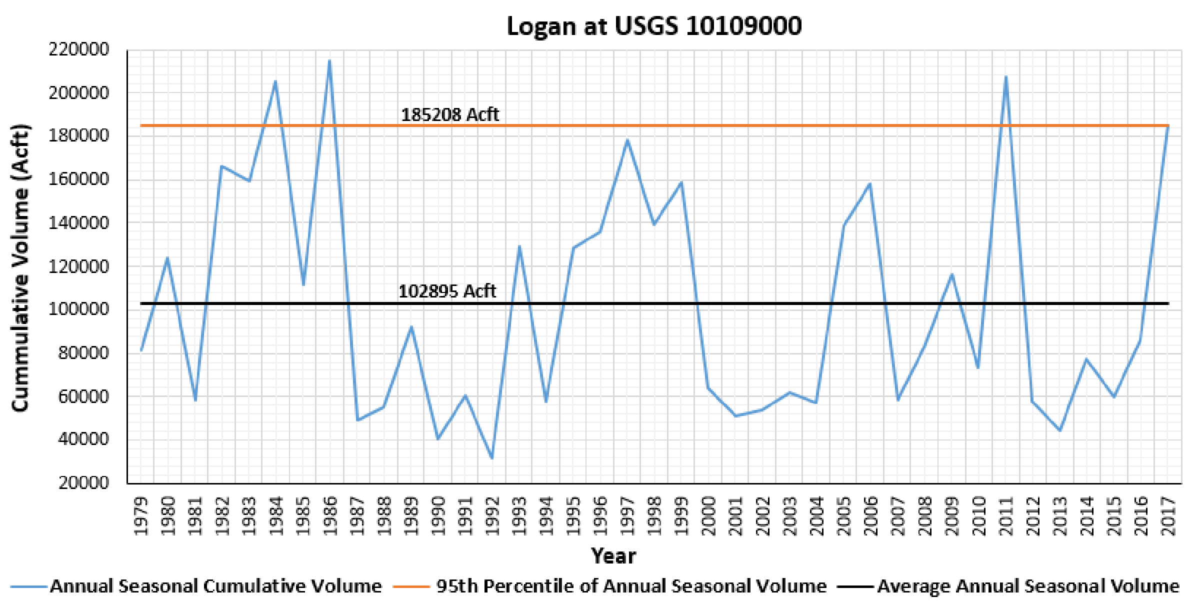
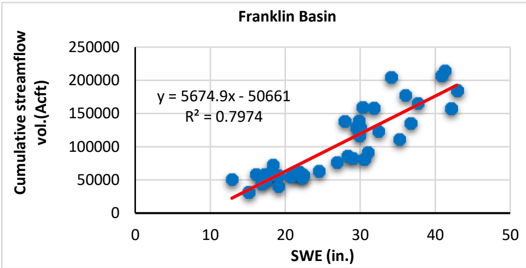
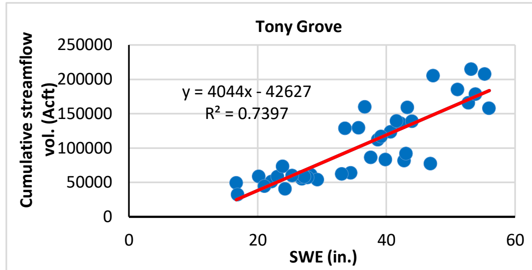
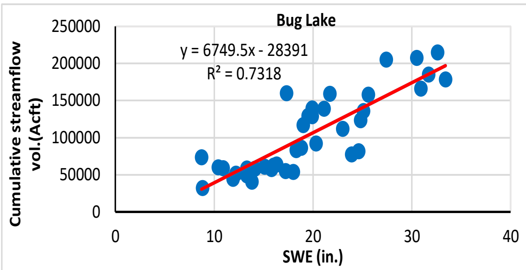


Figure 6. *Example of observed seasonal cumulative streamflow for 1979 to 2017 at Logan Station (USGS station: 10109000).*

An example of the established regression relationship between the seasonal streamflow volume and April 1 SWE values in the Logan project area is shown in Figure 7. Three SNOTEL stations (Franklin, Tony Grove, and Bug Lake) were considered for regression with the 95th percentile of annual seasonal streamflow volume. The results show a strong linear relationship between the April 1 SWE values ($R^2 > 0.70$) and the cumulative volume of the streamflows. The tabulated SWE indices, derived from the regression analysis, define the cloud seeding suspension values for each of the SNOTEL stations (see more discussions in the summary and recommendation section). Further analysis and results for each of the cloud seeding projects are presented in the next section.







SNOTEL stations	95% of the sesonal volume (Acft)	Criticla SWE values for April 1st (in.)
Franklin Basin	185208	41.56
Tony Grove	185208	56.38
Bug Lake	185208	31.65

Figure 7*. Linear regression between the April 1 SWE values at the three SNOTEL stations and the 95th percentile of the cumulative volume of the seasonal streamflows at the Logan Station.*

3. Analysis of the Suspension Criteria

The historical daily streamflows derived from the USGS website were used to calculate the annual seasonal cumulative volume of streamflow. The monthly SWE values of the SNOTEL stations were extracted from the NRCS website. The following section presents the results of the streamflow characteristics (seasonal cumulative streamflow, mean of the volume, and the 95th percentile of the mean value), the regression equations of the seasonal streamflow volume, SWE values of the SNOTEL stations, and SWE indices derived to suspend the cloud seeding projects.

3.1 Northern Utah

The northern Utah cloud seeding project includes the Logan, Weber, and Dunn Creek basins, as shown in Figure 1. The results of analysis for each of the basins are summarized below.

3.1.1 Logan River Basin

The cumulative seasonal streamflow volume for the Logan basin at the Logan Station was derived from the daily historical streamflows observed at the USGS 10109000 streamgage from 1979 to 2017. Figure 8 presents the time series of annual seasonal cumulative streamflows (blue line), mean volume of the flow (black line), and critical streamflow volume (red line) that correspond with the 95th percentile of the streamflow volume. As shown, the mean volume of the seasonal flow is 102,895 ac-ft, the standard deviation is 53283, and the 95th percentile volume of the seasonal streamflow as 185,208 ac-ft.

As shown, the annual streamflows cross the critical flow line in 1984, 1986, 2011, and 2017 – which are the historical wet years observed in the basin. The critical flow level observed in the past was also compared with the historical flood levels. The NWS website provides a summary of the flood categories and observed floods in the last 100 years. Based on the available records, the four flood categories classified in the basins are major flood stage: 6.0 feet; moderate flood stage: 5.5 feet; action stage: 5.0 feet; and low stage: 0.0 feet. The records show that the highest flood stage ever reached was 7.50 feet in 1907; another six events cross the action stage (6.50 feet in 1984, 5.80 feet in 1983, 5.70 feet in 1986, 5.30 feet in 1999, and 4.90 feet in 2005). It is noted that all the flood events were experienced in the months of May and June and within a three-week window. This may be due to the combined effects of the high elevation snowmelt and heavy rainfall.

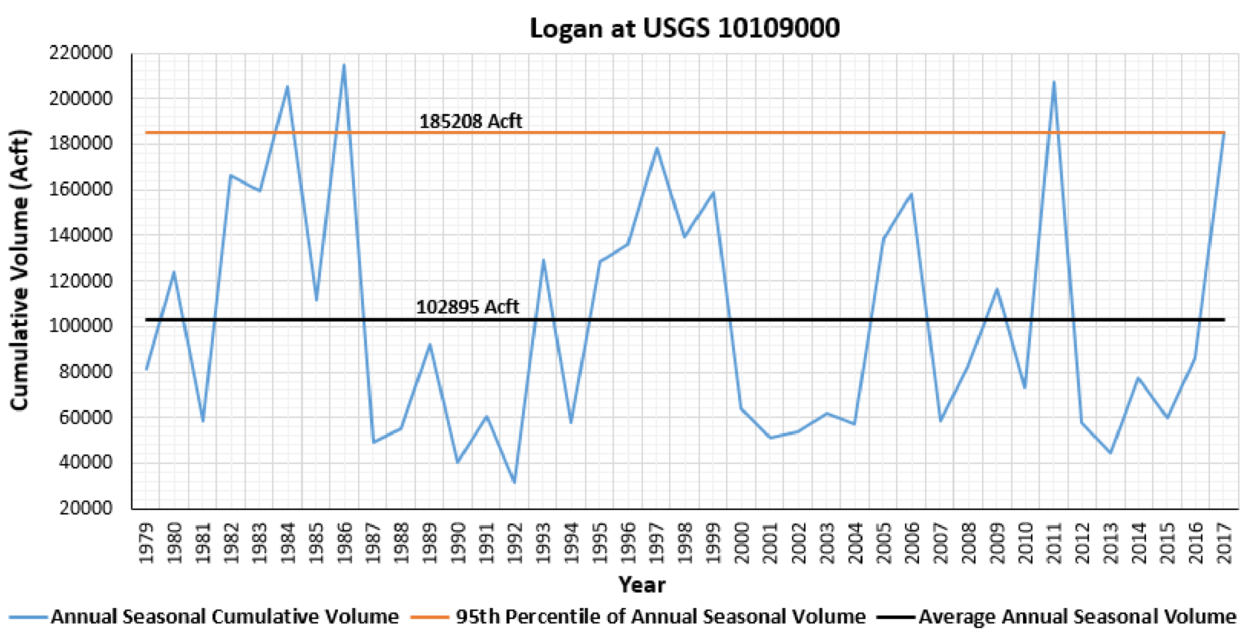


Figure 8*. A time series plot of the annual cumulative volume of the seasonal streamflows, mean value, and the 95th percentile of the mean based on the USGS streamgage record at Logan Station.*

Figure 9 presents historical records of the annual peak streamflow at the gaged station. Most of the flooded years are consistent with the record high of the average maximum flows. Comparing the potential suspension years (marked by the red line in Figure 8) and the observed flood events (NWS records, Figure 9 peaks), there are a few years where suspension may have eliminated the flooding events; however, it cannot be ensured that risks of flooding will be avoided after adopting the SWE indices in the Logan basin.

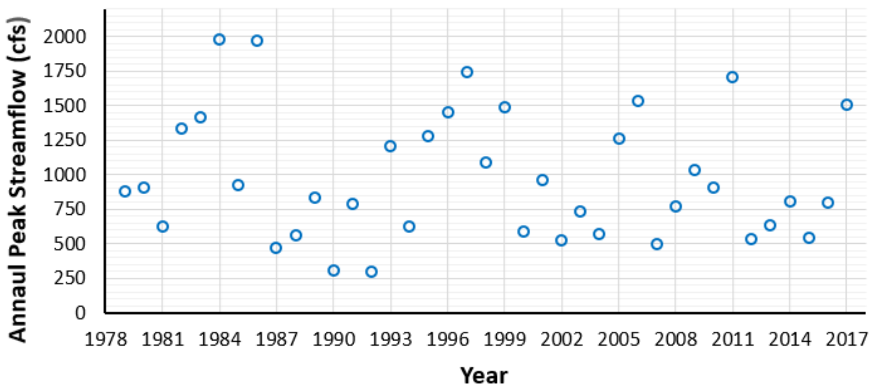
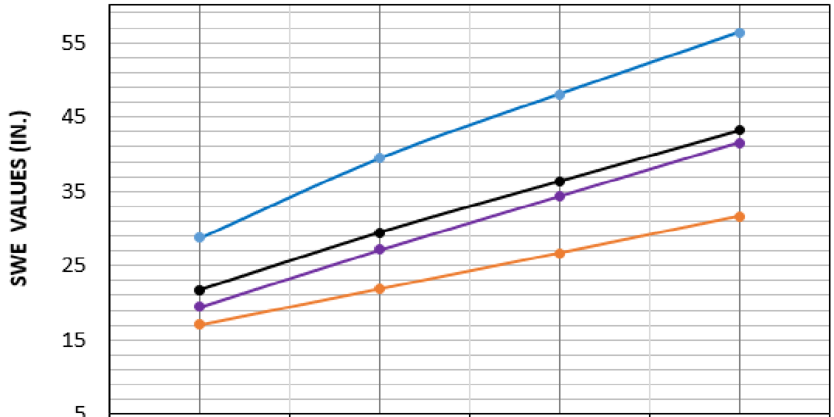


Figure 9. *Peak streamflow at the USGS 10109000 Logan River near Logan.*

The three SNOTEL stations considered for this basin are Franklin Basin (in Idaho), Tony Grove, and Bug Lake, which have SWE values records available since 1979. The linear regression equations were derived for each of the SNOTEL sites and the critical streamflows for each month. As presented in Table 1A (see appendices), most of the regression equations have R^2 greater than 0.70 on April 1 and March 1, whereas the R^2 varies from 0.41 to 0.65 on January 1 and February 1, respectively, indicating an acceptable statistical range. Based on the statistics of the stepwise regression results of April 1, the ranking of the SNOTEL stations for this basin will be Franklin Basin ($R^2 = 0.797$ and $p < 0.05$), Tony Grove ($R^2 = 0.739$ and $p < 0.05$), and Bug Lake ($R^2 = 0.731$ and $p < 0.05$). The derived regression equations as shown in Table 1A (see appendices) were applied to generate the suspension SWE indices for all the SNOTEL stations and the critical streamflows (Figure 10). A daily suspension SWE index value for any SNOTEL station can be derived by a linear interpolation between any two monthly values.



	SWE Jan 1st (in.)	SWE Feb 1st (in.)	SWE March 1st (in.)	SWE April 1st (in.)
Tony Grove	28.73	39.44	48.06	56.34
Bug Lake	17.08	21.91	26.72	31.65
Franklin Basin, Idaho	19.50	27.14	34.35	41.56
Average	21.77	29.50	36.37	43.18

***Figure 10**. SWE based suspension indices values for three SNOTEL stations in the Logan River Basin.*

3.1.2 Weber River Basin

The cumulative seasonal streamflow volume for the Weber basin near Oakley was derived from the daily historical streamflows observed at the USGS 10128500 streamgage from 1979 to 2017. The mean volume of the seasonal flow is 114,192 ac-ft, the standard deviation is 91262, and the 95th percentile volume is 176,179 ac-ft.

The four SNOTEL stations considered for this basin are Hayden Fork, Smith Morehouse, Trial Lake, and Chalk Creek, which have SWE values records available from 1979 to 2017. The linear regression equations were derived for each of the SNOTEL sites and the critical streamflows for each month. As shown in Table 2A (see appendices), most of the regression equations have R^2 values ranging from 0.40 to 0.70 on April 1 and March 1, whereas R^2 varies from 0.30 to 0.59 on January 1 and February 1, respectively. As discussed, the ranking of the SNOTEL stations based on statistical performance are Chalk Creek ($R^2 = 0.739$ and $p < 0.05$); Trail Lake ($R^2 = 0.651$ and $p < 0.05$); Smith Morehouse ($R^2 = 0.541$ and $p < 0.05$); and Hayden Fork ($R^2 = 0.394$ and $p < 0.05$).

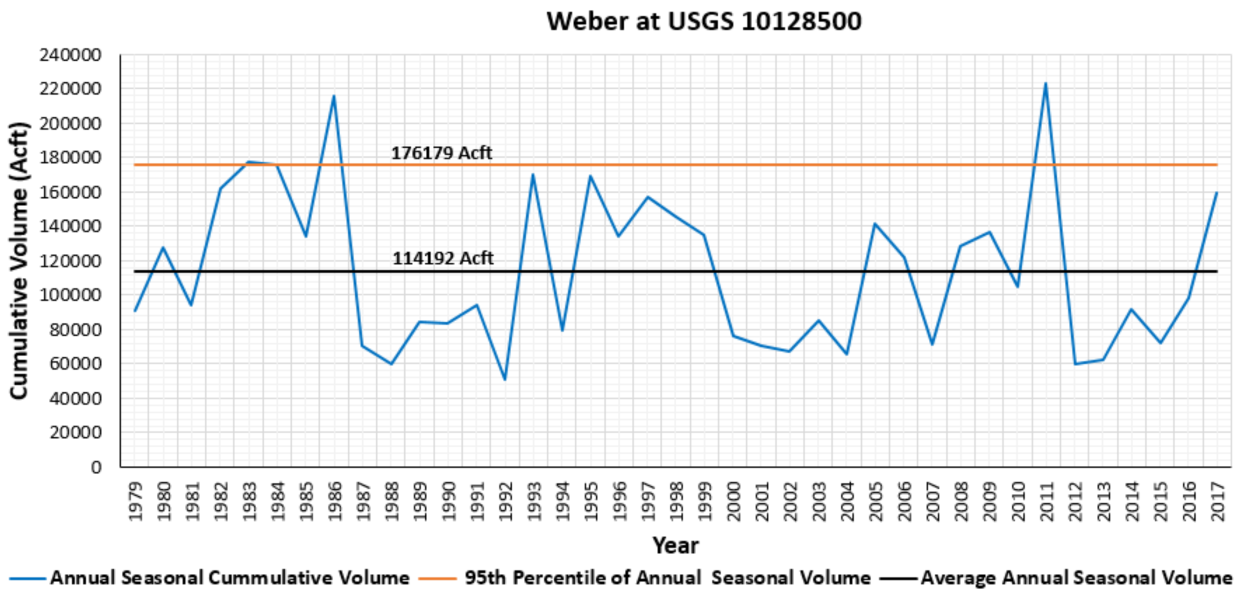


Figure 11. *A time series plot of the annual cumulative volume of the seasonal stream flows, mean value and the 95th percentile of the mean based on the USGS streamgage for the Weber Basin near Oakley.*

Based on the available records of the NWS, five flood categories classified in this basin are major flood stage: 29.0 feet; moderate flood stage: 28.0 feet; flood stage: 27.0 feet; action stage: 25.0 feet; and low stage: 0.0 feet. Figure 12 shows the historical annual maximum flow observed at the same location. The records show that the river had a crest level above 24.0 feet in 2006, 1999, 2005, and 1985. The years 1983, 1986, and 2011 are also the years with maximum flow observed at the gaged station. It is noted that all flood events were experienced in the months of April, May, and June. Similar to the other basins, the critical flow will not avoid the risks of flooding below the streamgage point.

The regression equations as presented in Table 2A (see appendices) were considered to generate the suspension SWE indices values for all the SNOTEL stations and the critical streamflows (Figure 13). All the SWE values linearly increase from January to April (in Figure 13: January, February, March, and April are labeled as 1, 2, 3, and 4 respectively). The tabulated values are the specific SWE indices values derived from the regression equations. A daily suspension SWE indices values for any SNOTEL station can be derived by a linear interpolation of the two values of the plot.

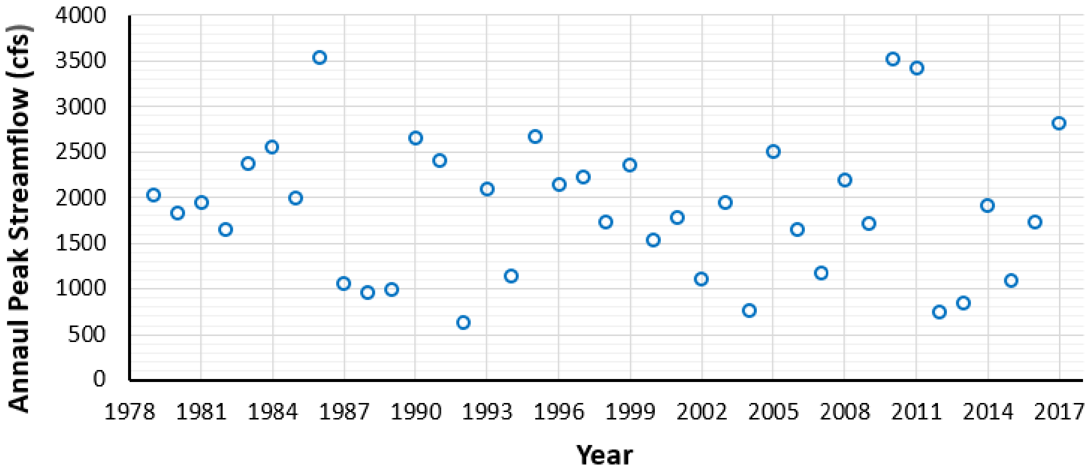
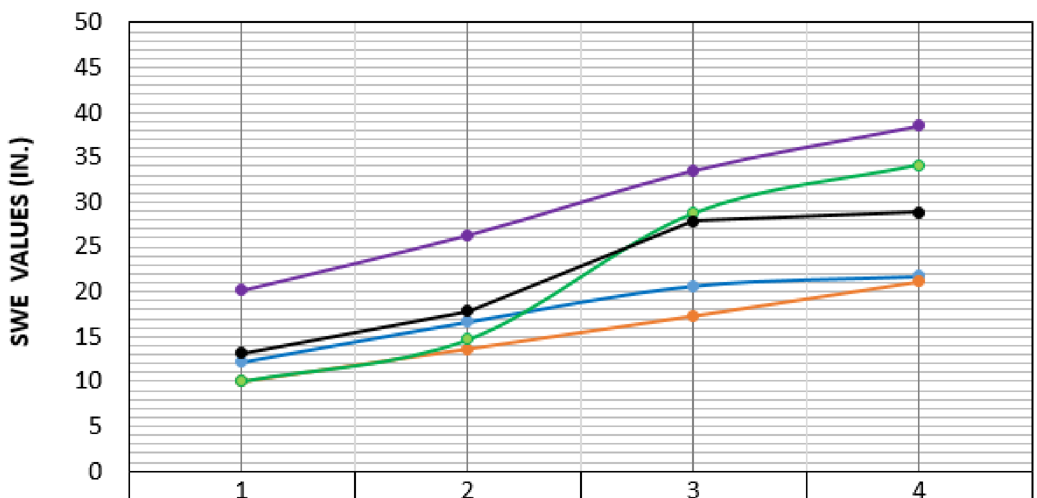


Figure 12. *Peak streamflow at the USGS 10128500 Weber River near Oakley.*



	1	2	3	4
Hayden Fork	12.19	16.69	20.71	21.79
Smith Morehouse	10.06	13.69	17.36	21.17
Trial Lake	20.15	26.33	33.55	38.54
Chalk Creek #1	10.09	14.73	28.77	34.15
Average	13.12	17.86	27.85	28.91

Figure 13. *SWE based suspension indices values for three SNOTEL stations for the Weber River Basin*.

3.1.3 Dunn Creek River Basin

The cumulative seasonal streamflow volume for the Dunn Creek Basin near Park Valley was derived from the daily historical streamflows observed at the USGS 10172952 streamgage from 1979 to 2017 (Figure 14). The Dunn Creek Basin has a relatively lesser catchment area (about 8.72 square miles) and corresponding flow characteristic. The mean value of the calculated seasonal flow volume is 2,914 ac-ft, the standard deviation is 2396, and the 95th percentile volume of the seasonal streamflow is 5,733 ac-ft. receptively. The results of this Dunn Creek Basin analysis will be used to represent Box Elder County area and nearby project areas as there are not such other streamgage and nearby SNOTEL stations to better represent the Box Elder County project areas.

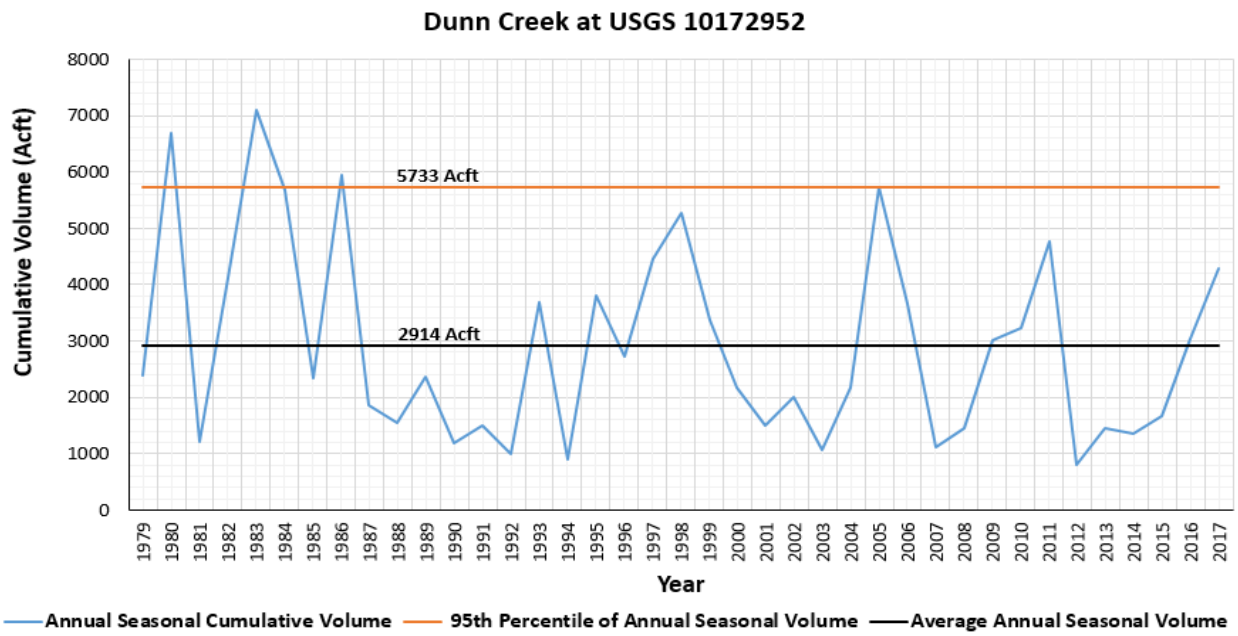


Figure 14. *A time series plot of the annual cumulative volume of the seasonal stream flows, mean value and the 95th percentile of the mean based on the USGS streamgage for the Dunn Creek Basin near Park Valley.*

The two SNOTEL stations considered for the analysis are Howell Canyon (in Idaho), and George Creek. The Howell Canyon SNOTEL station was used due to proximity to the project areas and has SWE records available from 1979 to 2017. Other SNOTEL stations available within the catchment areas were not considered, as the SWE records at these stations are available only since 2011. The linear regression equations derived for each of the SNOTEL sites and the critical streamflows for each month are presented in Table 3A (see appendices). The calculated regression results have R^2 values ranging from 0.40 to 0.68 on April 1 and March 1, respectively, whereas the R^2 varies from 0.24 to 0.68 on January 1 and February 1, respectively. Statistically, George Creek shows a strong correlation to the Howell Canyon station. The ranking of the stations based on the statistical performances are George Creek ($R^2 = 0.684$ and $p < 0.05$) and Howell Canyon ($R^2 = 0.394$ and $p < 0.05$).

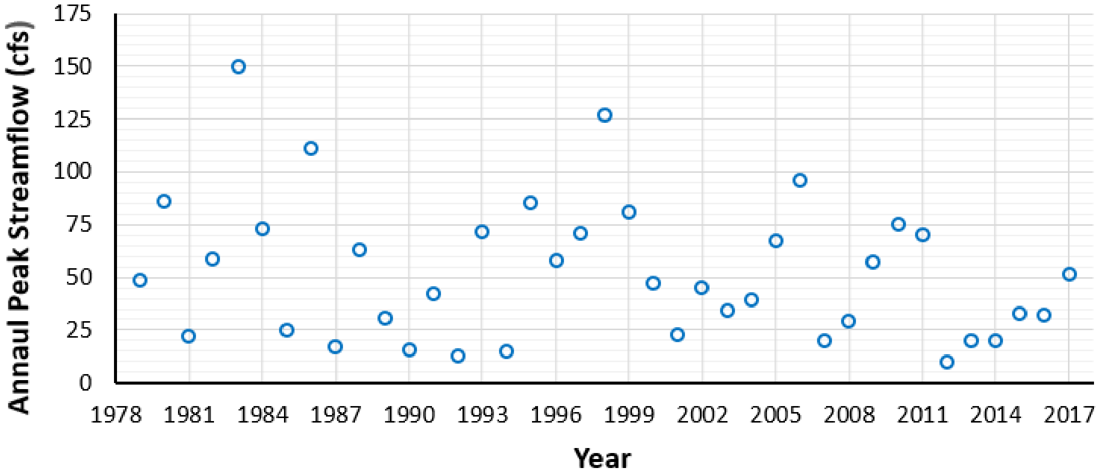
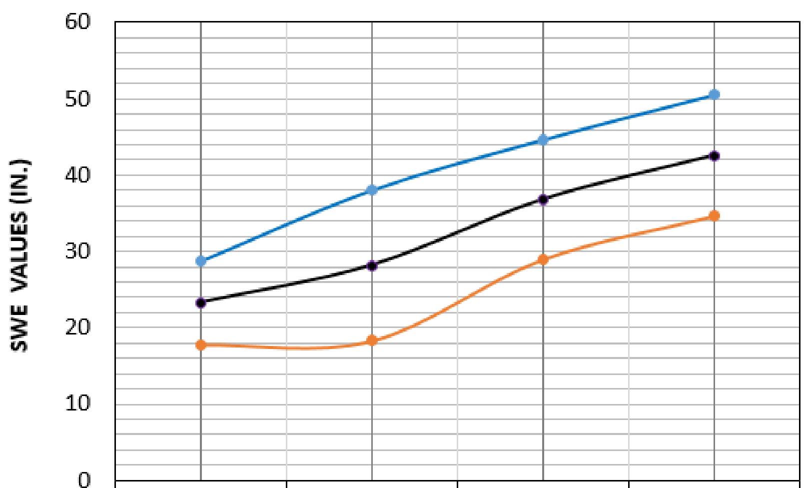


Figure 15. *Peak streamflow at the USGS 10172952 Dunn Creek near Park Valley*



	1	2	3	4
Howell Canyon, Idaho	28.71	38.00	44.59	50.46
George Creek	17.84	18.32	28.93	34.61
Average	23.28	28.16	36.76	42.54

Figure 16. *SWE based suspension indices values for three SNOTEL stations for the Dunn Creek basin near Park Valley.*

Unlike other basin, there are not any data available on the NWS website about the flood risk level nearby of the gage station. Figure 15 shows the maximum annual flow observed in the past based on the USGS data source. The 95th percentile flow line (Figure 14) suggest that 1980,1983,1986, and 2005 are the seeding suspension years, which is also consistent compared to the historical maximum flow observed at the gage station (Figure 15).

The regression equations as shown in Table 3A (see appendices) were considered to generate the SWE indices values for the critical streamflows (red line in Figure 14). The tabulated values (Figure 16) show the specific SWE indices values derived for each of the SNOTEL stations and average values in the basin. A daily suspension SWE indices value of any one of the two SNOTEL stations can be derived by linearly interpolating the critical SWE indices plot of the Dunn Creek basin.

3.2 Central and Southern Utah

The five river basins studied in the Central and Southern cloud seeding project area include Sevier Basin, Coal Creek, Virgin River, Santa Clara River, and South Willow Creek. The results of the analysis of each of the river basins are presented in the following section.

3.2.1 Sevier River Basin

The cumulative seasonal streamflow volume for the Sevier River Basin at Hatch was derived from the daily historical streamflows observed at the USGS 10174500 streamgage from 1979 to 2017. Based on the observation, the mean volume of the seasonal flow is 51,716 ac-ft, the standard deviation is 41662, and the 95th percentile volume is 120,473 ac-ft. (Figure 17). The annual streamflows cross the critical flow line in 1980, 1983, 2005, and 2011.

The historical flooding events and peak flows were also evaluated using the data from the NWS and USGS sources. The NWS records classify five types of flood based on the flood stage: major flood: 4.70 feet; moderate flood stage: 4.30 feet; flood stage: 3.90 feet; action stage: 3.50 feet; and low stage: 0.0 feet. The records show that the highest flood stage ever reached was 5.11 feet in 1971, and another five events cross the action stage in 1983 (4.36 feet), 1931 (4.11 feet), 1993 (3.80 feet) and 2003 (3.68 feet). All the flooding events were observed in the months of May and June, except a 1971 flood in December. The summer floods may be due to the combined effects of the high elevation snowmelt and heavy rainfall. Figure 18 shows historical records of the annual peak streamflow observed at the gaged station based on the USGS source. The highest peaks of the streamflows year coincides with critical flows shown in Figure 17 (i.e., years: 1980, 1983, 2005, and 2011), however the flood risks in the Sevier Basin cannot be avoided when applying the SWE indices-based suspension criteria.

The three SNOTEL stations considered for this basin are Castle Valley, Harris Flat, and Farnsworth Lake, which have SWE values records available from 1979. The linear regression equations were derived for each of the SNOTEL sites and the critical streamflows for each month (Table 5). The stepwise regression results rank the SNOTEL stations: Castle Valley (R^2 = 0.718 and $p < 0.05$), Harris Flat (R^2 = 0.691 and $p < 0.05$), and Farnsworth Lake (R^2 = 0.324 and $p < 0.05$), respectively.

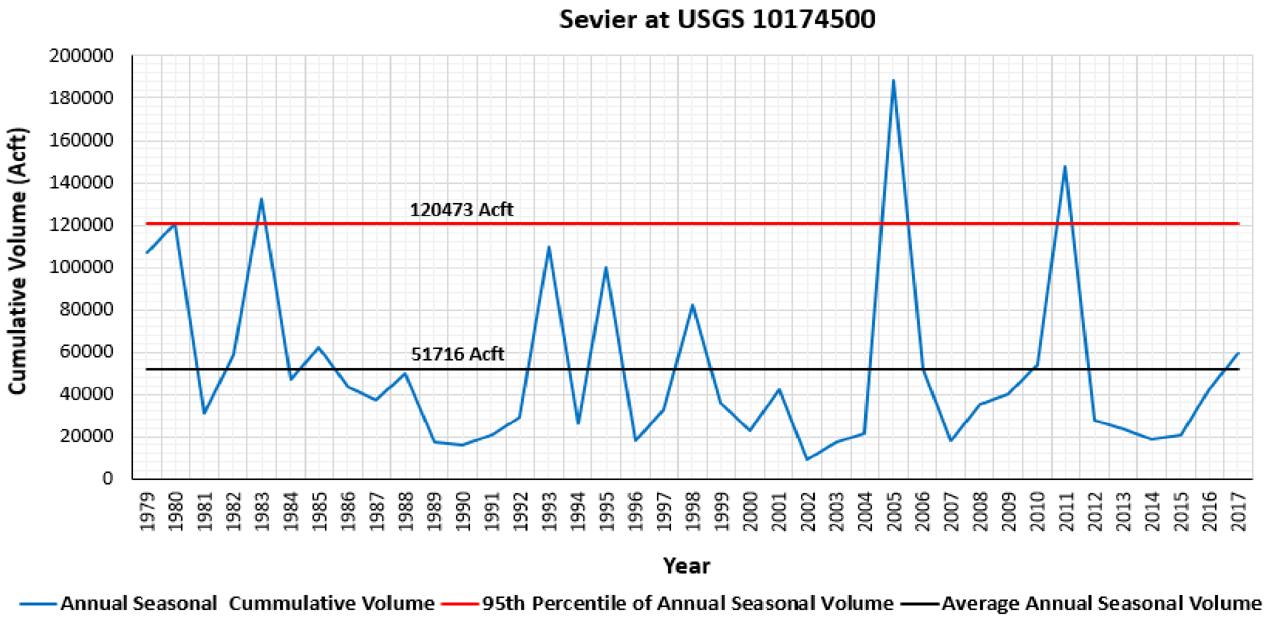


Figure 17. *A time series plot of the annual cumulative volume of the seasonal streamflows, mean value and the 95th percentile of the mean based on the USGS streamgage for the Sevier Basin at Hatch.*

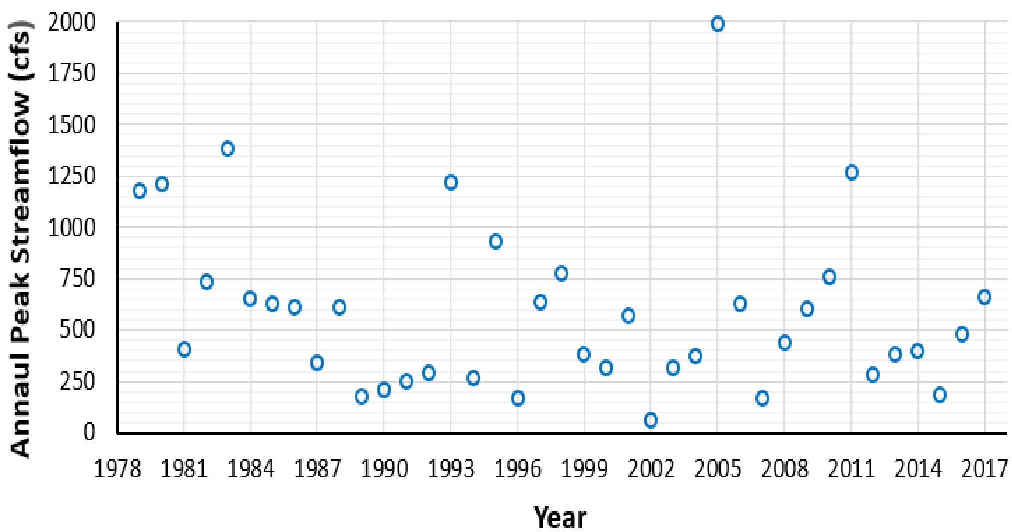
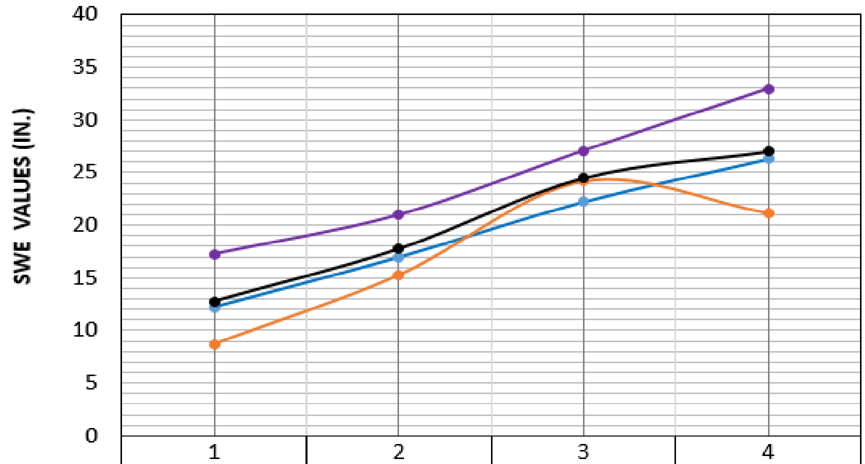


Figure 18. *Peak streamflow at the USGS 10174500 Sevier River at Hatch.*



	1	2	3	4
Castle Valley	12.23	16.96	22.22	26.30
Harris Flat	8.71	15.25	24.16	21.15
Farnsworth Lake	17.25	20.96	27.05	32.93
Average	12.73	17.72	24.48	27.00

Figure 19*. SWE based suspension indices values for three SNOTEL stations in the Sevier River Basin.*

The derived regression equations, as shown in Table A4 (see Appendices), were applied to generate the suspension SWE indices values for each SNOTEL station and an average of the stations (see Figure 19). As shown, all the SWE values increase from January to April except the Harris Flat Station. Similar to other basins, a daily suspension SWE indices values for any SNOTEL station can be derived by linear interpolation of the two values.

3.2.2 Coal Creek Basin

The cumulative seasonal streamflow volume for the Coal Creek Basin near Cedar City was derived from the daily historical stream flows observed at the USGS 10242000 streamgage from 1979 to 2017. The calculated streamflow characteristics for this basin are presented in Figure 20. The annual seasonal streamflow volume crosses the critical flow line in 1983, 1993, 2005, and 2011, which are recorded wet years.

There are no flood observation stations nearby Coal Creek that are managed by the NWS. The historical records of the maximum annual peak values of the streamflows, based on the USGS source, are shown in Figure 21. The suspension years (i.e., 1983, 1993, 2005, and 2011) indicated by the calculated critical flow (Figure 20) are within the maximum range but does not exactly match the observed maximum values (Figure 21). The results indicate that observed maximum peak flows may be due to rainfall rather than snowfall and snowmelt, and the potential flood events will not be avoided by the suspension criteria.

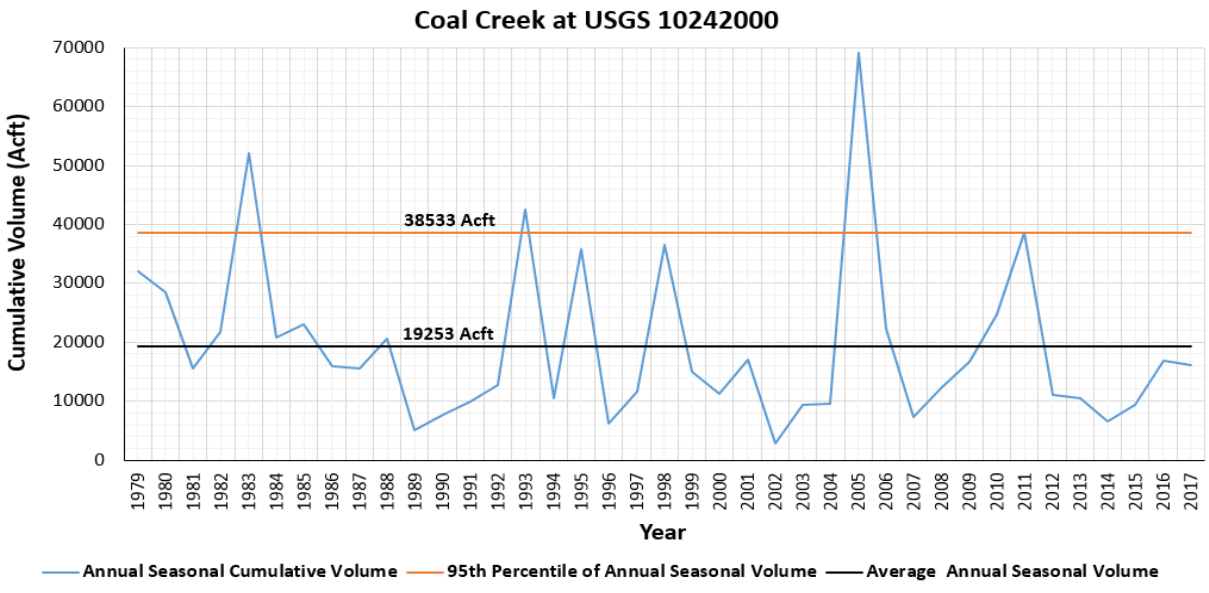


Figure 20. *A time series plot of the annual cumulative volume of the seasonal streamflows, mean value and the 95th percentile of the mean based on the USGS streamgage for the Coal Creek Basin near Cedar City.*

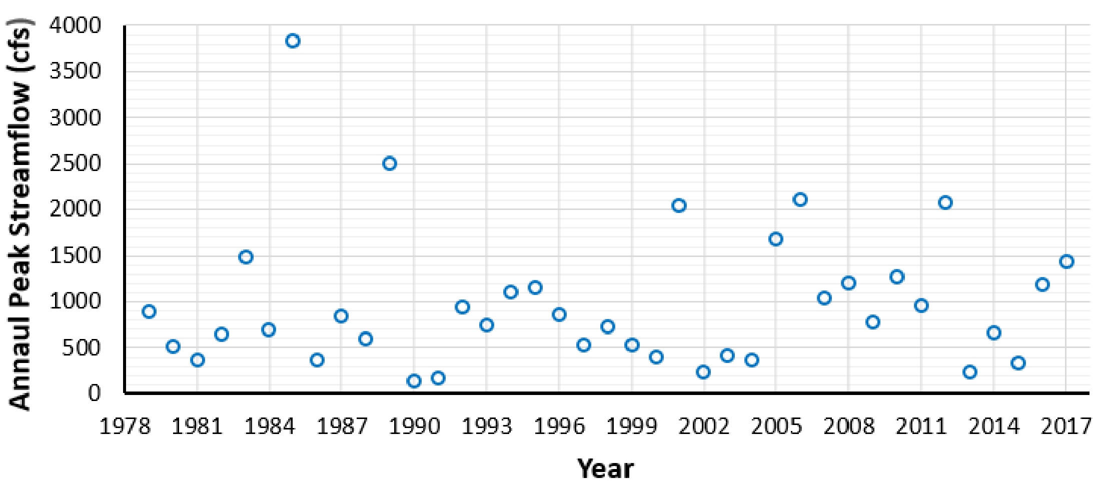
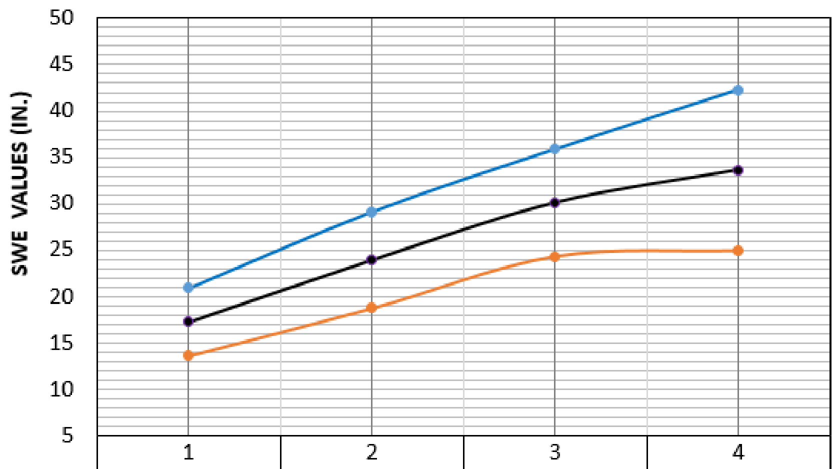


Figure 21. *Peak streamflow at the USGS 10242000 Coal Creek near Cedar City.*



	1	2	3	4
Midway Valley	20.89	29.12	35.89	42.29
Webster Flat	13.57	18.70	24.30	24.93
Average	17.23	23.91	30.10	33.61

Figure 22*. SWE based suspension indices values for three SNOTEL stations for Coal Creek Basin.*

The two SNOTEL stations considered for the analysis are Midway Valley and Webster Flat. Both have SWE values records available since 1981. Linear regression equations were derived for each of the SNOTEL stations from the critical streamflows (see Table A5: Appendices). As presented, R^2 values range from 0.40 to 0.87, and ranking of the SNOTEL stations based on the stepwise regression results are Midway Valley ($R^2 = 0.867$ and $p < 0.05$) and Webster Flat ($R^2 = 0.717$ and $p < 0.05$). The results of the suspension SWE indices derived from the regression equations are shown in Figure 22. A daily suspension SWE indices value for any SNOTEL station can be derived by a linear interpolation of the two results.

3.2.3 Virgin River Basin

The cumulative seasonal streamflow volume for the Virgin River Basin at Virgin was derived from the daily historical stream flows observed at the USGS 09406000 streamgage from 1979 to 2017. The calculated seasonal volume, average, and 95th percentile of the streamflow volume is shown in Figure 23. The annual seasonal streamflow volume crosses the critical flow line in years: 1979, 1983, 1993, 2005, and 2011 respectively. The NWS does not maintain flood records at or near by the gage. Figure 24 shows the peak annual flow at the gaged station based on the USGS data source. Comparing the historical peak flow with Figure 23, most of the observed peak flows are nearly the same as the suspension years (1979, 1983, 1993, 2005, and 2011). The basin has a significantly large drainage area (i.e., 956 sq. miles) and will have the combined effects of snowmelt as well as rainfall to generate the peak and flooding.

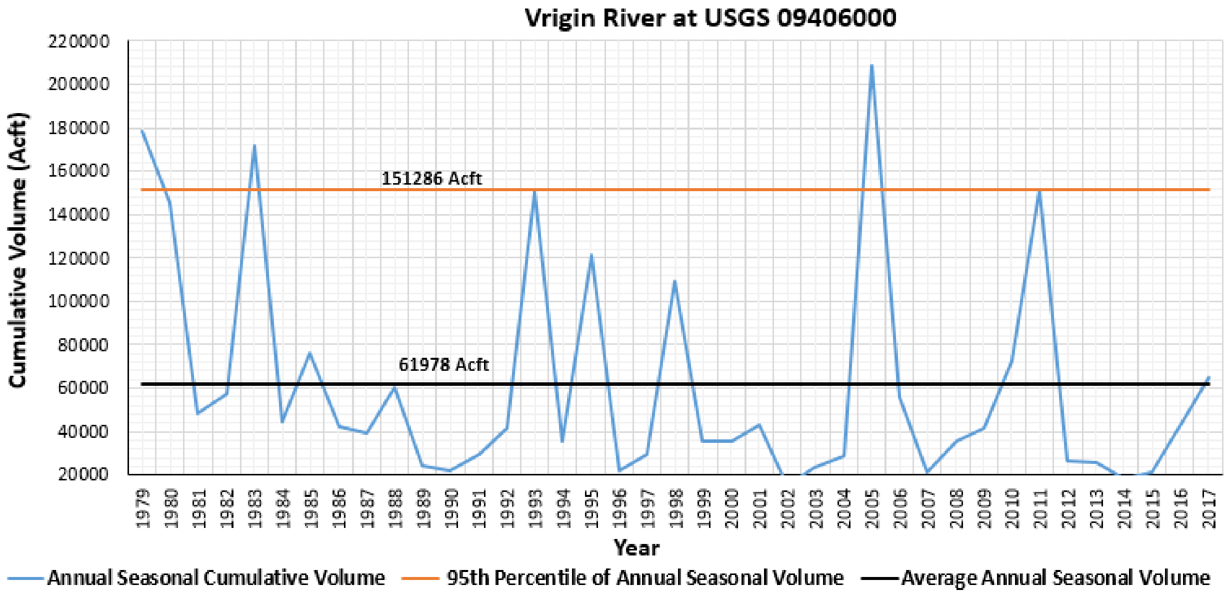


Figure 23. *A time series plot of the annual cumulative volume of the seasonal streamflows, mean value, and the 95th percentile of the mean based on the USGS streamgage for the Virgin River Basin at Virgin.*

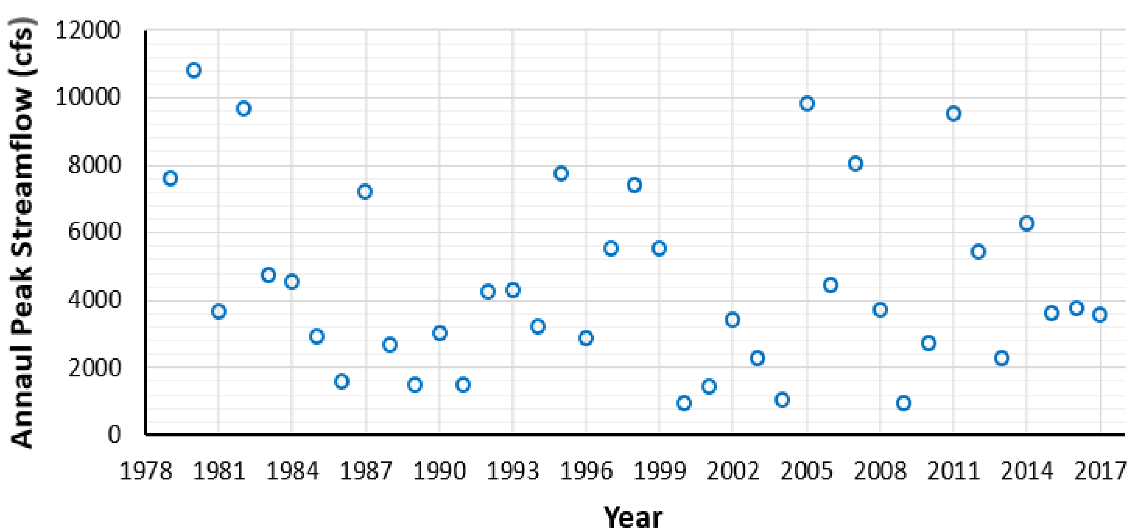
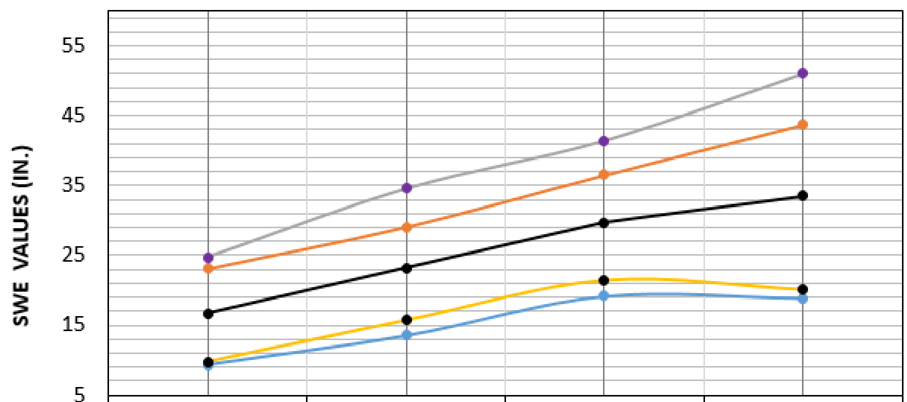


Figure 24. *Peak streamflow at the USGS 09406000 Virgin River at Virgin.*

The four SNOTEL stations considered for the SWE analysis are Long Flat, Kolob, Midway Valley, and Harris Flat. Linear regression equations were derived for each of the SNOTEL stations from the critical streamflows (see Table 6A -Appendices). As presented, R^2 values on April 1st range from 0.491 to 0.740, which are statistically acceptable. The ranking of the SNOTEL stations based on the stepwise regression are Kolob (R^2 = 0.742), Harris Flat (R^2 = 0.662), Midway Valley (R^2 = 0.546), and Long Flat (R^2 = 0.492), respectively.

Using the derived regression equations, the SWE indices values for all the SNOTEL stations and average values in the basin are shown in Figure 25. A daily suspension SWE index value for any of the four SNOTEL stations can be derived from Figure 25 by a linear interpolation of the SWE indices.



	SWE Jan 1st (in.)	SWE Feb 1st (in.)	SWE March 1st (in.)	SWE April 1st (in.)
Long Flat	9.38	13.54	19.20	18.91
Kolob	23.11	29.08	36.51	43.71
Midway Valley	24.76	34.56	41.44	51.05
Harris Flat	9.71	15.69	21.46	20.11
Average	16.74	23.22	29.65	33.44

Figure 25*. SWE based suspension indices values for three SNOTEL stations for the Virgin River basin.*

3.2.4 Santa Clara River Basin

The cumulative seasonal streamflow volume for the Santa Clara River Basin above Baker Reservoir was derived from the daily historical streamflows observed at the USGS 09409100 streamgage from 1989 to 2017. The calculated streamflow characteristics for this basin are presented in Figure 26. Unlike other streamgage stations, this location has extreme annual variability, indicating negligible seasonal flows (e.g., 1996, 2003, 2007, and 2013) in some years to extremely high seasonal flows other years (e.g., 1995, 2005 and 2011). The critical flow derived from the analysis is 11.620 ac-ft with the mean flow of 3,934 ac-ft. The annual seasonal streamflow volume crosses the critical flow line in 1995, 2005, and 2011 (Figure 26).

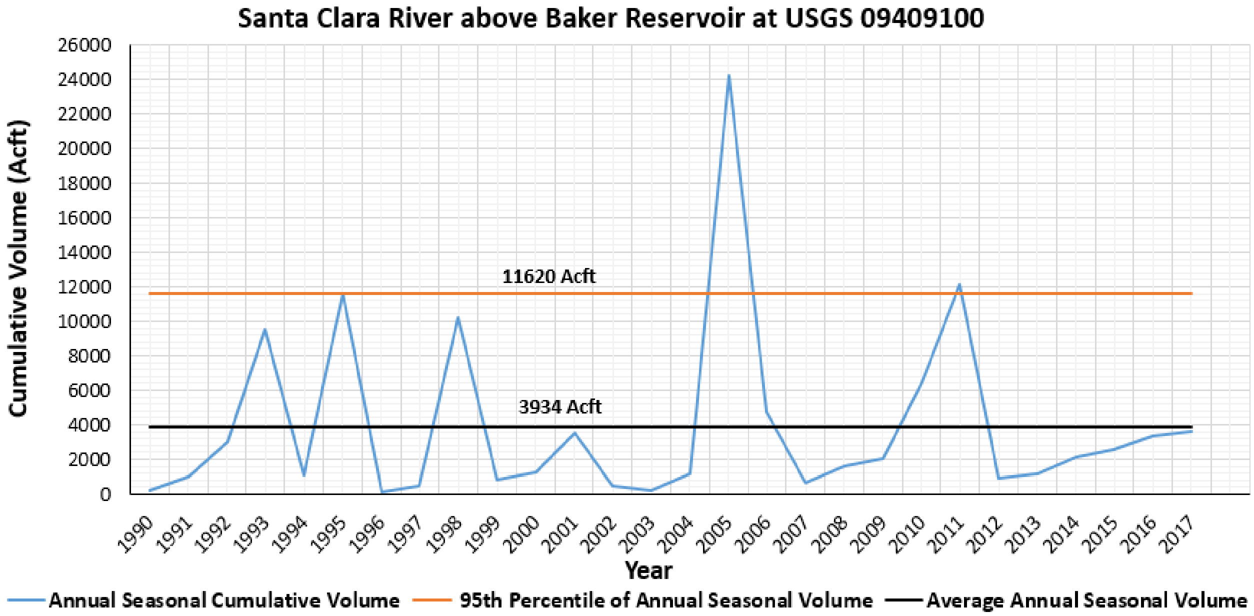


Figure 26*. A time series plot of the annual cumulative volume of the seasonal streamflows, mean value, and the 95th percentile of the mean based on the USGS streamgage for the Santa Clara River Basin above Baker Reservoir.*

The NWS records do not hold any flood observation information for this station. Based on the USGS sources, the historical maximum annual peak flow is shown in Figure 27. Interestingly, the maximum peak flow of years 1995, 2005, and 2011 (Figure 27) align with the critical flow years derived from Figure 26. This basin has a relatively small catchment area (about 116 sq. miles) and the basin is situated mostly in a low elevation range. It is likely that the basin has rain-dominated precipitation that generates a quick runoff at the observation gage. Most of the high peaks (e.g., 1995, 2005, and 2011) are avoided by the proposed suspension criteria, however it is suggested that the potential flood events will not be avoided by the suspension criteria.

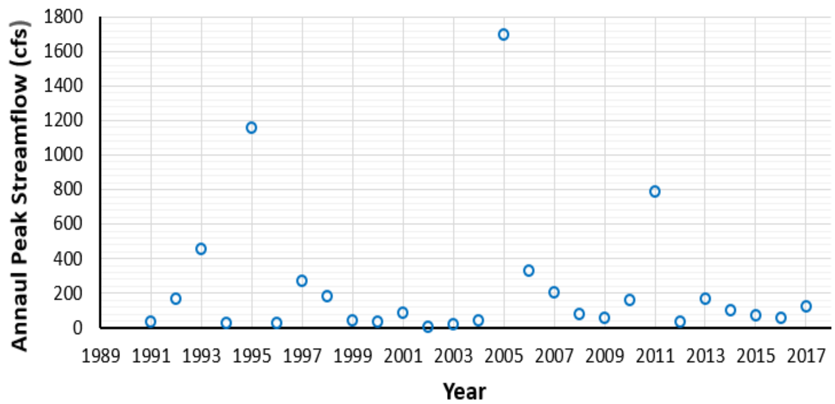
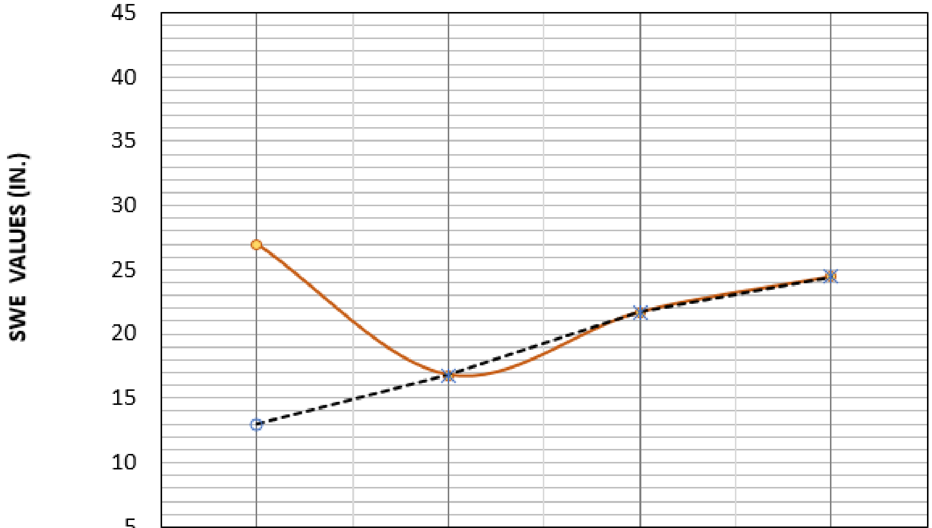


***Figure 27**. Peak streamflow at the USGS 09409100 Santa Clara River above Baker Reservoir.*

The four SNOTEL stations considered for the analysis were Little Grassy, Gardner Peak, Long Flat, and Kolob. All SNOTEL stations have SWE records available since 1989 except for the Gardner Peak station, which has SWE records available since 2005. Linear regression equations were derived for each of the SNOTEL stations from the critical streamflows (see Table 7A – Appendices). Except the Gardner Peak station, the other three SNOTEL stations have very poor regression results, and therefore were not included for further analysis (see Table 7A). The poor correlations might be due to the rain-dominated precipitation in the basin and/or the river basin being fed by low elevation watersheds.

Based on the statistical results (Table 7A) and critical flow, only Gardner Peak was evaluated for the suspension criteria (Figure 28). The SWE indices derived for Jan 1st seems "off" compared to the normal trends of the other SNOTEL stations. A trend line was extrapolated to derive average SWE indices for each of the months. The results show that most of the SNOTEL stations do not have a satisfactory level of statistical performances. As mentioned, the streamflows in this basin are likely dominated by the rainfall rather than snowfall or due to early snow melt in the lower elevations. The results of the regression and SWE indices suggest that other factors such as reservoir levels, forecasts of heavy rain on snow events, soil moisture and early season's streamflow levels should be critically evaluated to suspend the cloud seeding.



	SWE Jan 1st (in.)	SWE Feb 1st (in.)	SWE March 1st (in.)	SWE April 1st (in.)
Gardner Peak	26.96	16.82	21.70	24.45
Extrapolated Line	13.00	16.82	21.7	24.45

Figure 28. *SWE based suspension indices values for three SNOTEL stations for Santa Clara River basin.*

3.2.5 South Willow Creek Basin

The cumulative seasonal streamflow volume for the South Willow Creek River Basin near Grantsville was derived from the daily historical stream flows observed at the USGS 10172800 streamgage from 1979 to 2017. The mean volume of the seasonal flow is 3,129 ac-ft, the standard deviation is 1,586 ac-ft, and the 95th percentile of the annual cumulative volume is 5,426 ac-ft (Figure 29). The annual streamflows cross the critical flow line in 1984, 1998, and 2011.

The basin has a smaller-sized catchment area of about 4.19 square miles, and there are no NWS-managed flood observation stations near the South Willow Creek streamgage site. Figure 30 shows the historical annual maximum peak streamflow record at the gaged station derived from the USGS source. It is noted that critical years (Figure 29) have had very high peak flows observed in the past (Figure 30), however the SWE based suspension criteria will not avoid the potential flooding events.

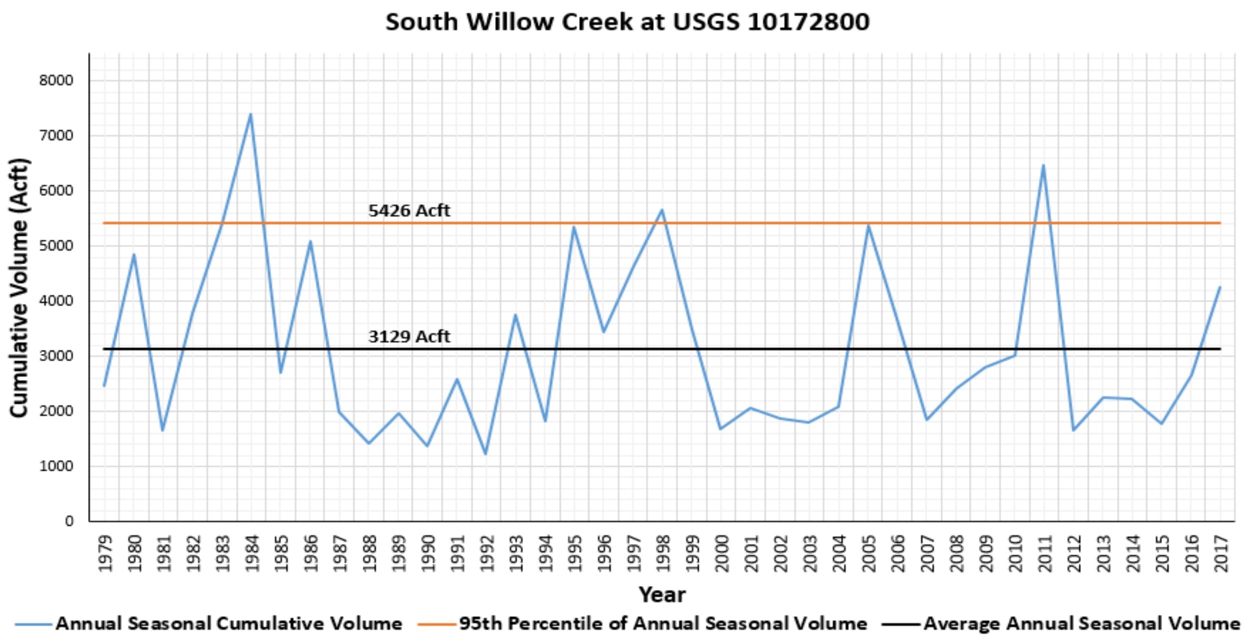


Figure 29. *A time series plot of the annual cumulative volume of the seasonal streamflows, mean of the cumulative seasonal flow, and the 95th percentile of the mean streamflow based on the USGS streamgage for the South Willow Creek Basin near Grantsville.*

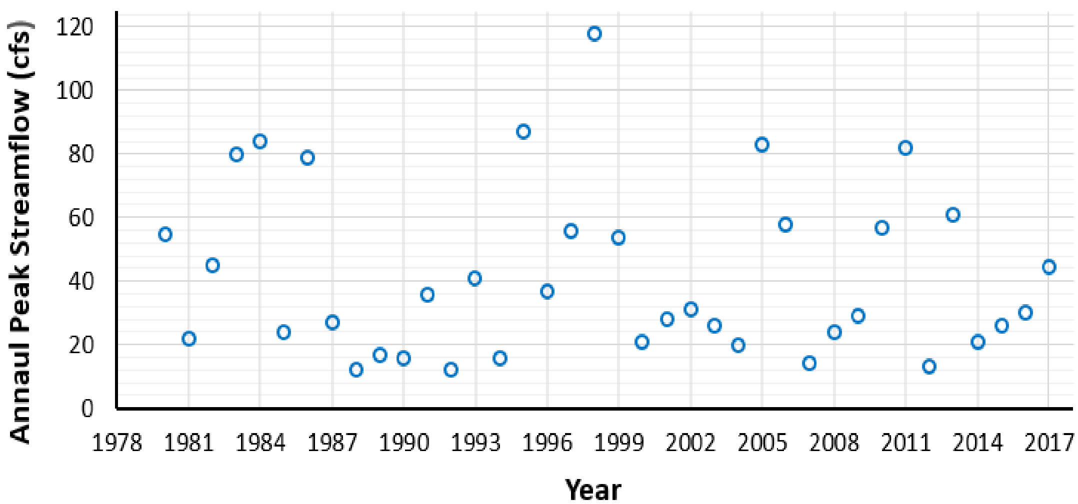
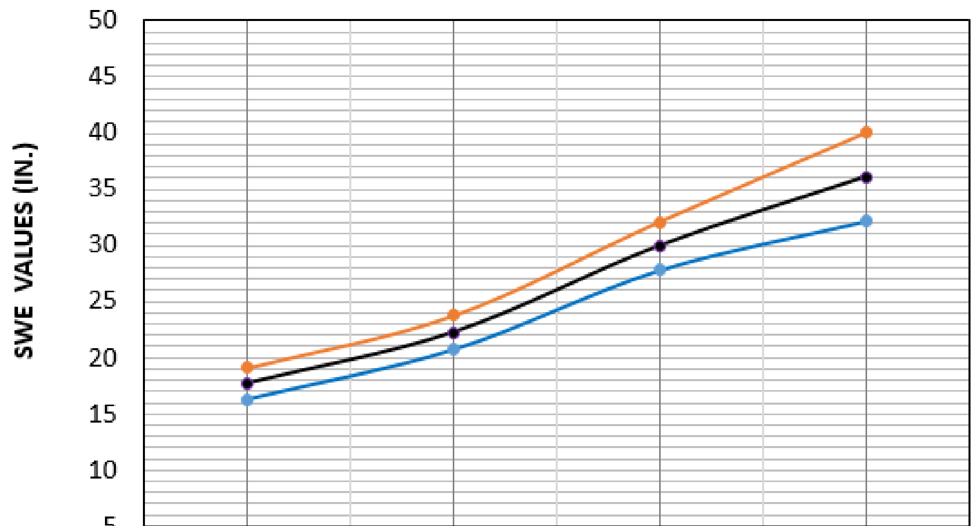


Figure 30. *Peak streamflow at the USGS 10172800 South Willow Creek near Grantsville.*

The two SNOTEL stations considered for the analysis are Mining Fork and Rocky Basin-Settlement**.** Linear regression equations were derived for each of the SNOTEL sites using the critical streamflows (see Table 8A -Appendices). The ranking of the SNOTEL stations based on the stepwise statistical results are Rocky Basin-Settlement ($R^2 = 0.645$ and $p < 0.05$) and Mining Fork ($R^2 = 0.640$ and $p < 0.05$).

The results of the suspension SWE indices derived from the regression equations and each of the SNOTEL stations are shown in Figure 31. As shown, all the SWE values linearly increase from January to April. A daily suspension SWE indices values for any SNOTEL station can be derived by a linear interpolation of the two results.



	1	2	3	4
Mining Fork	16.31	20.74	27.81	32.19
Rocky Basin Settlement	19.09	23.75	32.11	40.01
Average	17.70	22.25	29.96	36.10

Figure 31*. SWE based suspension indices values for three SNOTEL stations for the South Willow Creek Basin.*

3.3 Western and High Uintas

Three river basins were studied in the Western and High Uintas area, including upper Bear River, Duchesne River, and Provo River. The results of the analysis of each of the river basins are presented in the following sections.

3.3.1 Bear River Basin

The cumulative seasonal streamflow volume and other flow characteristics for the Bear River near the Utah-Wyoming state line was derived from the daily historical streamflows observed at the USGS 10011500 streamgage since 1979 (Figure 32). As shown, the annual streamflows cross the critical flow line in 1983, 1986, 1995, and 2011.

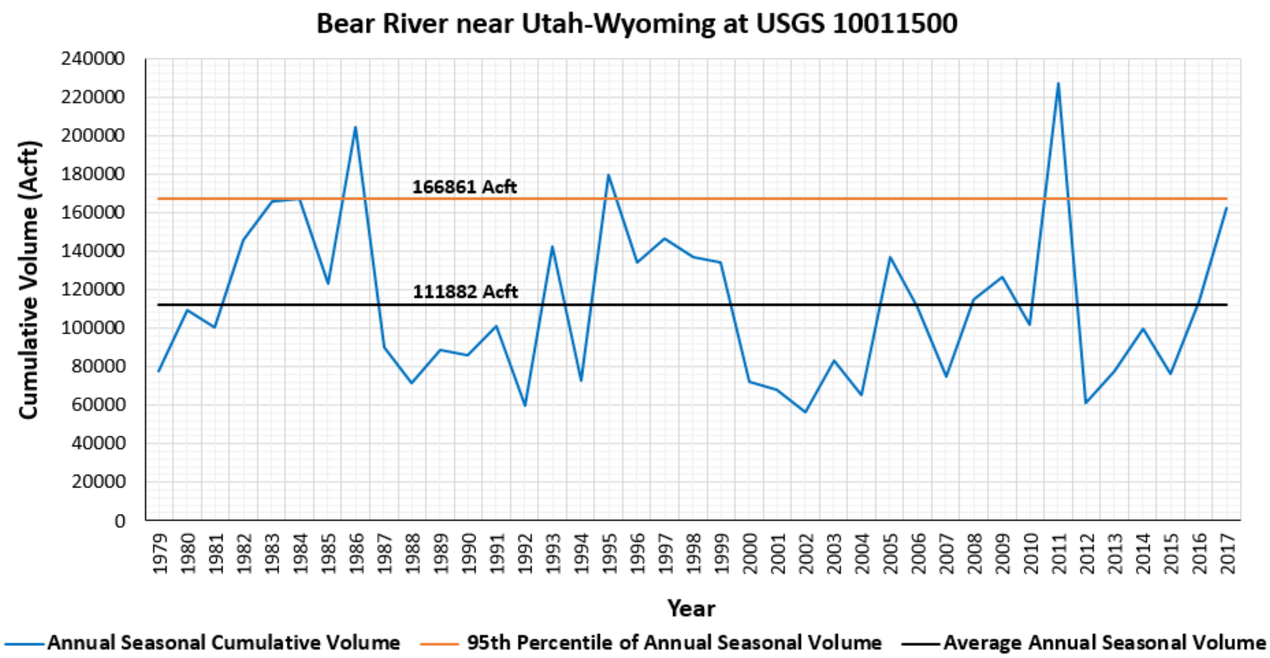


Figure 32. *A time series plot of the annual cumulative volume of the seasonal streamflows, the mean value, and the 95th percentile of the mean based on the USGS streamgage for the Bear River near the Utah/Wyoming state line.*

At the same gage station, the NWS records show the five flood categories: major flood stage: 9.50 feet; moderate flood stage: 9.0 feet; flood stage: 8.0 feet; action stage: 7.0 feet; and low stage: 0.0 feet. The highest seven flood events that crossed the 7.00 feet stage were in 2011 (7.82 feet), 2010 (7.72 feet), 2017 (7.70 feet), 2004 (7.40 feet), 1995 (7.40 feet), and 1990 (7.05 feet). Floods occurred in August, September, November, May, and June. The maximum annual peak flow at the same location based on the USGS records are shown in Figure 33. The critical years (Figure 32) have the highest peak flow observed in the past (compare Figure 34). The critical flow line may have coincidence with the maximum peak flows and observed flood events, however the critical line cannot avoid all the flood events in this basin.

The three SNOTEL stations considered for this basin are Hayden Fork, Lily Lake, and Trial Lake. All three SNOTEL stations have SWE data available since 1979. Monthly linear regression equations were derived for each of the SNOTEL sites based on the critical streamflows (Figure 34). The derived equations are presented in Table A9 (see Appendices). The ranking of the SNOTEL stations within this basin are: Lily Lake (R^2 = 0.731 and $p < 0.05$); Trial Lake (R^2 = 0.610 and $p < 0.05$); and Hayden Fork (R^2 = 0.378 and $p < 0.05$). All the SWE values increase except at the Hayden Fork station from March 1st to April 1st. It could be due to early snowmelt in the low-level elevation. A daily suspension SWE indices values for any SNOTEL station can be derived by linear interpolation of the two values.

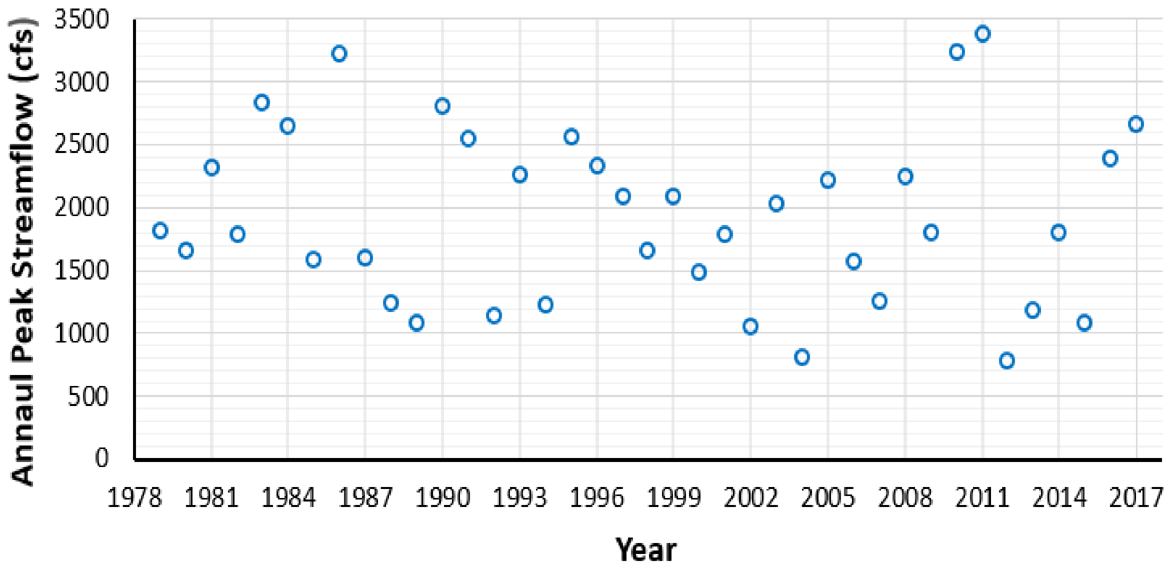
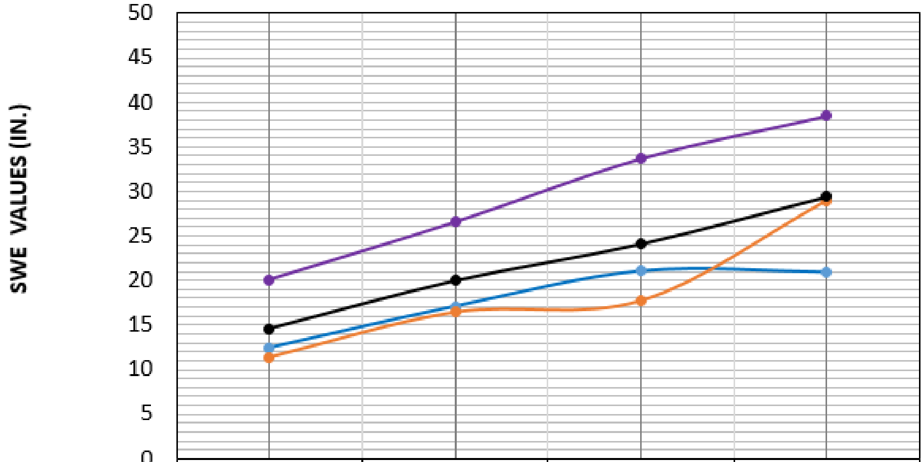


***Figure 33**. Peak streamflow at the USGS 10011500 Bear River near Utah-Wyoming state line*



	1	2	3	4
Hayden Fork	12.41	17.06	21.03	20.90
Lily Lake	11.38	16.40	17.69	28.93
Trial Lake	20.07	26.56	33.68	38.49
Average	14.62	20.01	24.13	29.44

Figure 34*. SWE based suspension indices values for three SNOTEL stations for the upper Bear River Basin.*

3.3.2 Duchesne River Basin

The cumulative seasonal streamflow volume and other streamflow characteristics for the Duchesne River near Tabiona was derived from the daily historical streamflows observed at the USGS 0927750 streamgage from 1979 to 2017 (Figure 37). The annual streamflows cross the critical flow line in 1983, 1986, and 2011.

The NWS manage flood observation data in the Duchesne River basin near Myton. The historical five flooding events observed in Myton were in 2005 (7.85 ft), 1999 (7.65 ft), 1986 (8.03 ft), 1983 (8.35 ft) and 1927 (10.42 ft). Most of the critical and observed flood events were in the months of April, May, and June, which may be due to escalated effects of snowmelt from the remote and high elevation mountains. The maximum peak streamflow observed in the past based on the USGS data is presented in Figure 38. It is notable that most of the flood events recorded by the NWS, maximum annual peak flow (Figure 38) and critical flow year (Figure 37) aligned in years 1983, 1986, and 2011. However, the SWE based indices will unlikely avoid all flooding events in this basin.

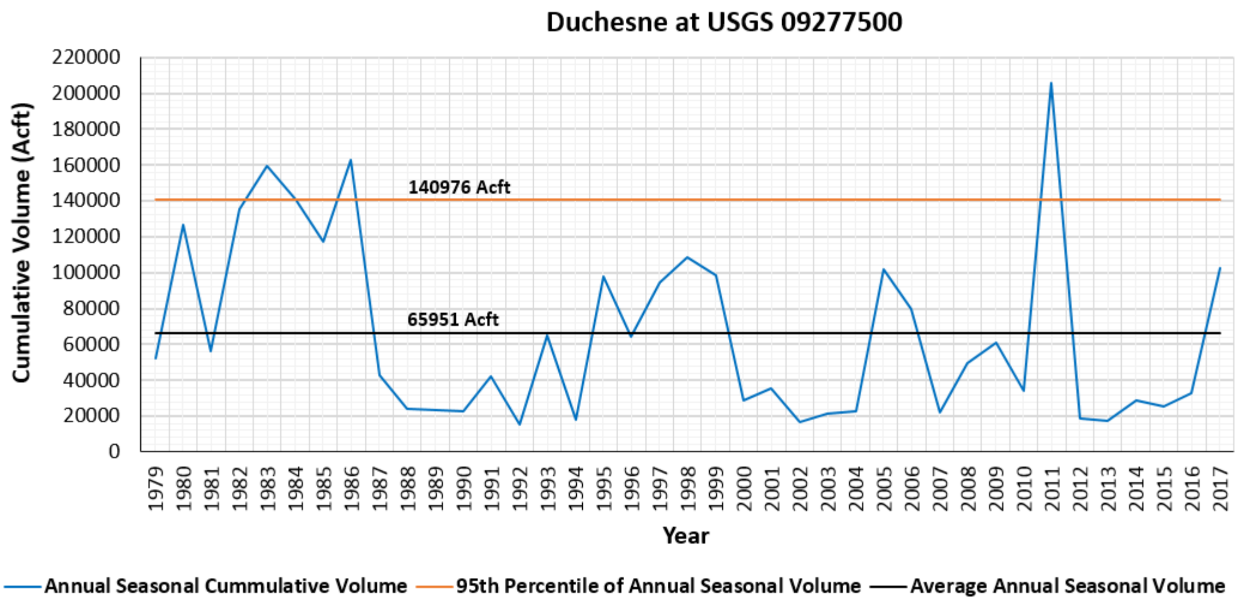


Figure 37. *A time series plot of the annual cumulative volume of the seasonal streamflows, mean value, and the 95th percentile of the mean based on the USGS streamgage for the Duchesne River near Tabiona.*

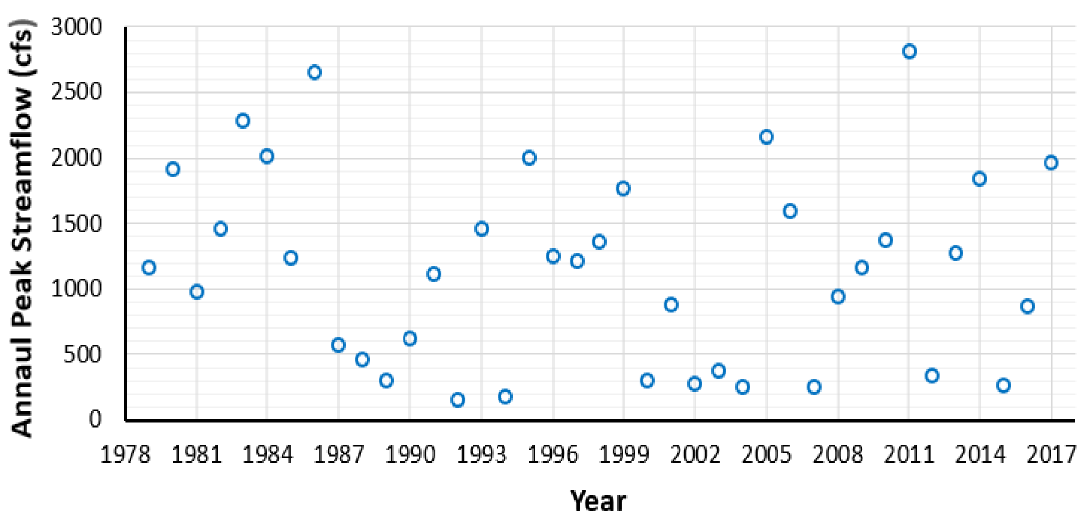
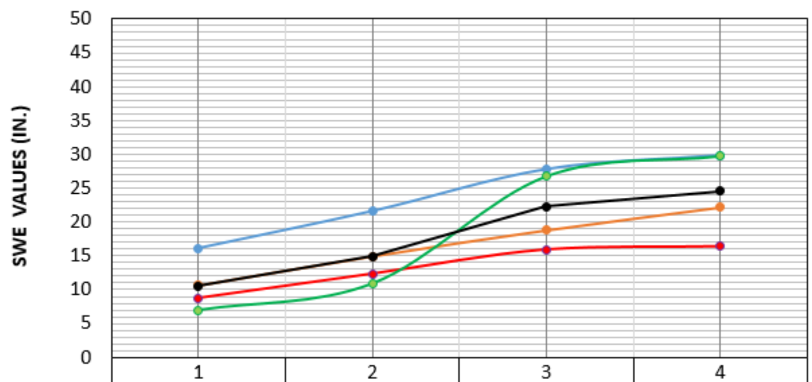


Figure 38. *Peak streamflow at the USGS 09277500 Duchesne River near Tabiona.*

The four SNOTEL stations considered for this basin are Daniels-Strawberry, Smith Morehouse, Rock Creek, and Strawberry Divide, which have SWE data available since 1979. The linear regression equations were derived for each of the SNOTEL sites using the critical streamflows (Table 10A - Appendices). Most of the regression equations haves R^2 value ranging from 0.52 to 0.61 (Table 10A), indicating a moderate statistical relationship. The ranking of the SNOTEL stations based on the stepwise regression for this basin are Strawberry Divide ($R^2 = 0.596$ and $p <$

0.05), Daniels-Strawberry ($R^2 = 0.588$ and $p < 0.05$), Smith Morehouse ($R^2 = 0.515$ and $p < 0.05$), and Rock Creek ($R^2 = 0.610$ and $p < 0.050$).

The results of the derived SWE indices to suspend cloud seeding using the regression equations (Table 10A) and SWE values of the SNOTEL stations are shown in Figure 39. The average values show representative results of the SNOTEL stations and daily suspension SWE indices values for any SNOTEL station can be derived by a linear interpolation of the two values of the plot.



	1	2	3	4
Daniels-strawberry	16.07	21.59	27.82	29.89
Smith Morehouse	10.61	14.95	18.82	22.22
Rock Creek	8.76	12.31	15.88	16.41
Strawberry Divide	6.92	10.87	26.77	29.75
Average	10.59	14.93	22.32	24.57

Figure 39. *SWE based suspension indices values for three SNOTEL stations for the Duchesne River basin.*

3.3.3 Provo River Basin

The cumulative seasonal streamflow volume and other flow characteristics for the Provo River near Woodland was derived from the daily historical streamflows observed at the USGS 10154200 streamgage from 1979 to 2017 (Figure 40). The annual seasonal streamflows cross the critical flow line (i.e., 95th percentile values) in years: 1986, 1995, 201, and 2017 respectively.

There is no specific NWS flood related database near the streamgage station. The historical records of the peak streamflow derived from the USGS observations are shown in Figure 41. The critical years 1995, 2011, and 2017 (Figure 40) are aligned with the observed maximum peak flows (Figure 41). Most of the observed peak flows were in the wet years (see Figure 40). However, it is noted that the SWE indices derived from the critical flow will not avoid all flood risks in the basin.

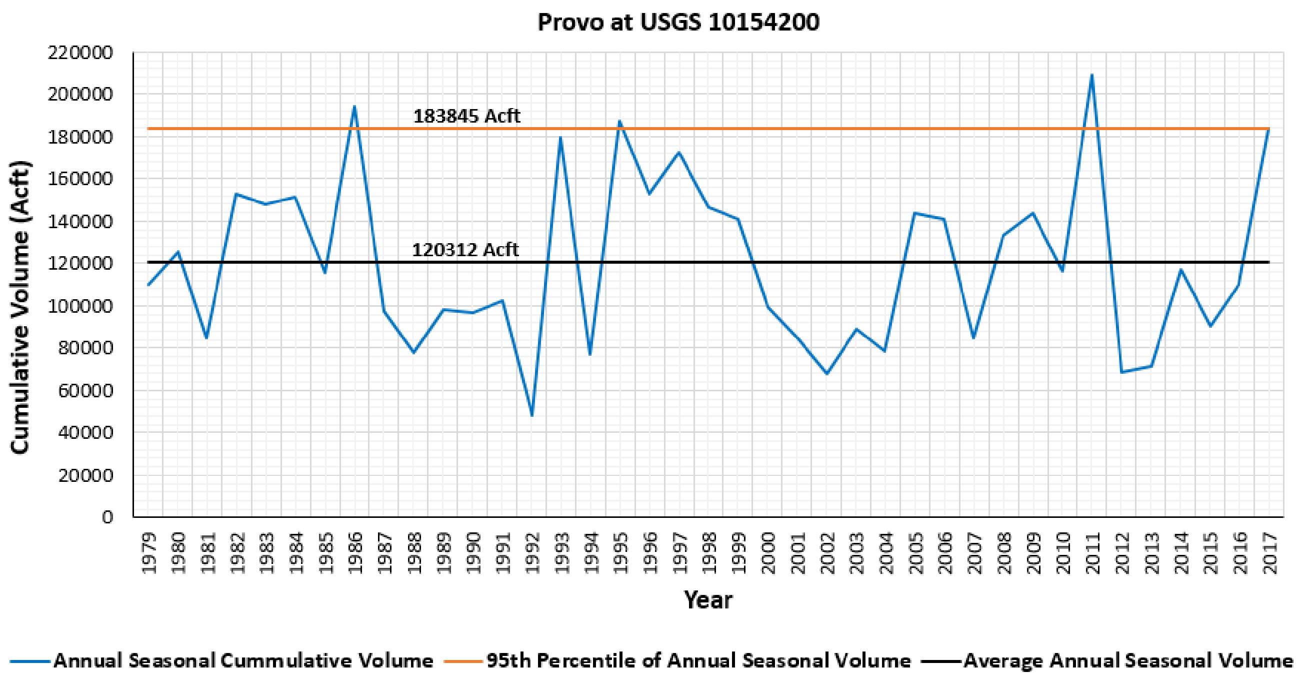


Figure 40. *A time series plot of the annual cumulative volume of the seasonal streamflows, mean value and the 95th percentile of the mean based on the USGS streamgage for the Provo River Basin near Woodland.*

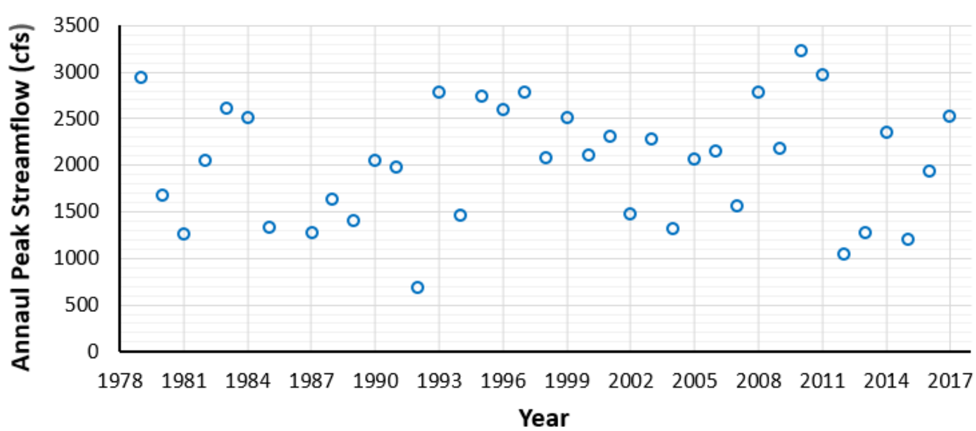
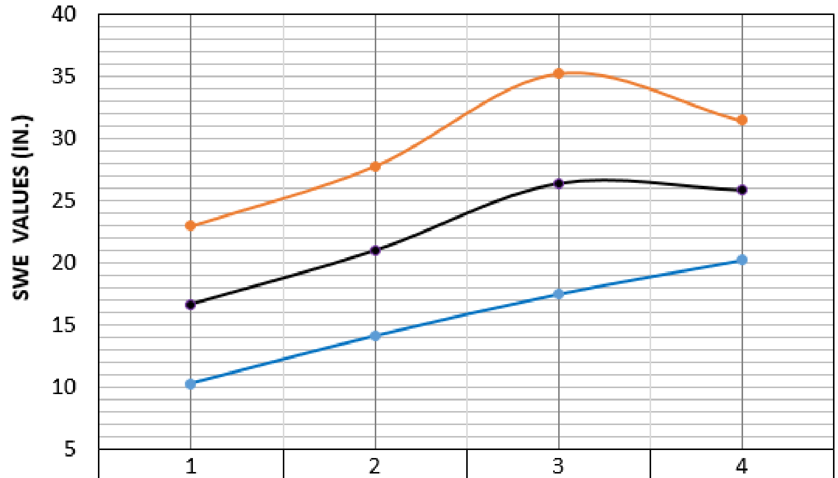


Figure 41. *Peak streamflow at the USGS 10154200 Provo River Basin near Woodland*

The two SNOTEL stations considered for this basin are Beaver Divide and Trial Lake. Both the stations have SWE records available since 1979. As presented in Table 11A (see Appendices), the linear regression equations were established for each of the SNOTEL sites using the critical streamflows for each month. As shown, the R^2 values range from 0.67 to 0.58. The ranking of the SNOTEL stations based on the stepwise regression results are Trial Lake ($R^2 = 0.674$ and $p < 0.05$) and Beaver Divide ($R^2 = 0.578$ and $p < 0.05$).

The results of the SWE indices derived from the regression equations presented in Table 11A for this basin are shown in Figure 42. It is noted that two SNOTEL stations are located in high and lower elevations; therefore, independent SNOTEL indices are recommended to compare to the average of the two stations. Using the results of Figure 42, a daily suspension SWE indices value can be obtained by the linear interpolation of the two values.



	1	2	3	4
Beaver Divide	10.29	14.11	17.45	20.18
Trial Lake	22.98	27.78	35.23	31.44
Average	16.64	20.95	26.34	25.81

Figure 42. *SWE based suspension indices values for three SNOTEL stations for the Provo River Basin near Woodland.*

4. Summary and Recommendations

4.1 Summary

The objectives of this report were to: (1) review and summarize the cloud seeding suspension criteria practiced in Utah and neighboring states of Utah such as Colorado, California, and Nevada; (2) evaluate the existing SWE based indices and establish a relationship between the SWE and streamflow in the cloud seeding projects; and (3) update and recommend the cloud suspension criteria in the project areas.

The statistical methods were adopted to establish relationships between SWE values and observed streamflows. Recognizing the fact that the main objective of cloud seeding is to augment water supply sources, the seasonal streamflow within a basin was considered as an indicator to establish the SWE indices. The indicator streamflow considered (defined as the critical streamflow) for the analysis is the 95th percentile value of the annual seasonal cumulative volume of streamflow (April 1 to July 31). The data used to calculate the seasonal cumulative volume for each of the basins were extracted from the USGS website (daily flow from 1979 to 2017). The main motivation for choosing the 95th percentile of seasonal volume was to augment the water supply sources in the seeding projects as much as possible, recognizing the fact that cloud seeding productivity in a basin will not exceed the augmented precipitation of 5% to 15%. It implies that cloud seeding will increase the seasonal streamflow roughly by 5%. It is noted that the historical streamflows data include the effects of the cloud seeding, as there are no reliable data sources that allow separating the effects of cloud seeding in the basins. Therefore, the 95^{th} percentile of the annual seasonal volume indirectly indicates the targeted cloud seeding goal.

The SNOTEL stations considered in this study are located within the catchment of each river basin, have long historical observational data records available (most of the SNOTEL stations have data since 1979), and have been continuously updated by the NRCS. The regression equations were established between the April - July cumulative runoff and SWE values from selected SNOTEL stations for the first day of January, February, March, and April. The SWE indices for each of the basins and SNOTEL stations were derived from the critical cumulative seasonal volume (which is the 95th percentile of the streamflow). The results of the critical streamflow, SWE index values, and related plots for each of the basins are presented in the Analysis section. The stepwise regression analysis was performed to rank the SNOTEL stations in the basins.

Table 2 presents a summary of the results for suspending cloud seeding projects in Utah. It includes information from the USGS stations, critical annual seasonal streamflow volumes (in ac-ft), SNOTEL stations considered for each of the basins, SWE index values for each station, percentage of monthly average SWE values (from January to April), and ranking of the SNOTEL stations. The ranking of the SNOTEL stations is based on the statistical results that reflect their contributions to generate streamflow. For example, in northern Utah seeding projects, the Logan River basin was considered for the analysis. The USGS streamgage station used for the Logan basin is Logan at Logan (USGS 10109000), which has a critical cumulative seasonal volume of 185,208 ac-ft (second column). The three SNOTEL stations analyzed for this basin are Franklin Basin (Idaho), Tony Grove, and Bug Lake. The next eight columns in the table show the results of the SWE indices and percentage of the mean value for each of the SNOTEL stations. The final column of the table indicates the ranking of the SNOTEL stations based on the stepwise regression results for the April 1 SWE values. The table also presents the average SWE percentage value for the basin (e.g., percentage of average calculated values are nearly: January 1: 205%, February 1: 174%, March 1: 160%, and April 1: 158%). For informational purposes, the average, standard deviation, and the 95th percentile range of the average value are also presented in the last rows of the table.

Table 2. *Summary of the results on the SNOTEL stations and average SWE indices in the major river basins of the cloud seeding project areas in Utah*

Project & Basin	Critical streamflow volume (Acft) & USGS streamgage ID	SNOTEL station	SWE value corresponding to the critical flow (in in. & %)								Ranking of SNOTEL stations
			Jan 1 (in.)	Jan 1 (%)	Feb 1 (in.)	Feb 1 (in %)	March 1 (in.)	March 1 (in %)	April 1 (in.)	April 1 (in %)	
1. Northern Utah Project	185208	Franklin Basin, Idaho	19.5	190.8	27.1	165.3	34.4	154.7	41.6	153.6	1
1.1 Logan at Logan	USGS 10109000	Tony Grove	28.7	205.9	39.4	175.6	48.1	160.4	56.3	156.6	2
		Bug Lake	17.1	218.8	21.9	180.3	26.7	165.3	31.6	162.7	3
		Average	**21.8**	**205.2**	**29.5**	**173.7**	**36.4**	**160.1**	**43.2**	**157.6**	
1.2 Weber near Oakley	176179	Chalk Creek #1	10.1	173.1	14.7	153.7	28.8	149.9	34.2	143.4	1
	USGS 10128500	Trial Lake	20.2	207.4	26.3	180.6	33.6	173.3	38.5	162.3	2
		Smith Morehouse	10.1	186.5	13.7	157.6	17.4	146.5	21.2	160.3	3
		Hayden Fork	12.2	194.2	16.7	172.1	20.7	158.6	21.8	164.6	4
		Average	**13.1**	**190.3**	**17.9**	**166.0**	**25.1**	**157.1**	**28.9**	**157.6**	
1.3 Dunn Creek near the Park Valley	5733	George Creek	17.8	187.8	18.3	143.8	28.9	163.4	34.6	153.8	1
	USGS 10172952	Howell Canyon, Idaho	28.7	280.0	38.0	223.2	44.6	206.0	50.5	191.7	2
		Average	**23.3**	**233.9**	**28.2**	**183.5**	**36.8**	**184.7**	**42.5**	**172.7**	
2. Western & High Uintah Project	166861	Lily Lake	11.4	202.7	16.4	194.1	17.7	147.4	28.9	139.2	1
2.1 Bear River near Utah - Wyoming state line	USGS 10011500	Trial Lake	20.1	206.5	26.6	182.3	33.7	173.9	38.5	162.1	2
		Hayden Fork	12.4	197.7	17.1	175.8	21.0	161.0	20.9	146.0	3
		Average	**14.6**	**202.3**	**20.0**	**184.1**	**24.1**	**160.8**	**29.4**	**149.1**	
2.2 Duchesne near Tabiona	140976	Strawberry Divide	6.9	239.2	10.9	199.3	26.8	178.8	29.8	179.1	1
	USGS 09277500	Daniels-strawberry	16.1	248.1	21.6	202.4	27.8	190.5	29.9	192.8	2
		Smith Morehouse	10.6	196.6	15.0	172.4	18.8	158.8	22.2	168.3	3
		Rock Creek	8.8	230.0	12.3	219.7	15.9	205.7	16.4	209.1	4
		Average	**10.6**	**228.5**	**14.9**	**198.4**	**22.3**	**183.5**	**24.6**	**187.3**	
2.3 Provo near woodland	183845	Trial Lake	23.0	236.5	27.8	190.6	35.2	181.6	31.4	132.4	1
	USGS 09277500	Beaver Divide	10.3	210.4	14.1	179.5	17.5	170.8	20.2	200.3	2
		Average	**16.6**	**223.5**	**20.9**	**185.1**	**26.3**	**176.2**	**25.8**	**166.3**	
3. Central Utah Project	120473	Castle Valley	12.2	244.1	17.0	203.0	22.2	187.7	26.3	180.0	1
3.1 Sevier near Hatch	USGS 10174500	Harris Flat	8.7	298.8	15.3	273.6	24.2	223.0	21.2	209.8	2
		Farnsworth Lake	17.3	218.1	21.0	186.0	27.1	182.2	32.9	167.0	3
		Average	**12.7**	**253.6**	**17.7**	**220.9**	**24.5**	**197.6**	**26.8**	**185.6**	
3.2 Coal Creek near Cedar City	38533	Midway Valley	20.9	215.7	29.1	194.0	35.9	177.0	42.3	168.0	1
	USGS 10242000	Webster Flat	13.6	232.5	18.7	198.0	24.3	184.6	24.9	181.1	2
		Average	**17.2**	**224.1**	**23.9**	**196.0**	**30.1**	**180.8**	**33.6**	**174.5**	
3.3 South Willow near Grantsville	5426	Rocky Basin-settlemnt	19.1	205.3	23.8	174.1	32.1	171.4	40.0	167.5	1
	USGS 10172800	Mining Fork	16.3	243.7	20.7	177.0	27.8	171.8	32.2	168.7	2
		Average	**17.7**	**224.5**	**22.2**	**175.6**	**30.0**	**171.6**	**36.1**	**168.1**	
	Utah State Average (%)			**219**		**187**		**174**		**169**	
	Standard deviation			**29**		**26**		**19**		**20**	
	Upper 95% (%)			**233**		**199**		**183**		**179**	
	Lower 95% (%)			**205**		**175**		**165**		**159**	

4.2 Discussion

The results of the SWE indices-based criteria derived from this study are similar to the existing SWE-based suspension criteria adopted in Utah. Unlike the existing practice of taking a single value for the entire state, it proposes basin/project specific SWE indices. In order to adopt the SWE index, it is necessary to monitor the SNOTEL observations updated on the NRCS website. Each of the SNOTEL stations has its specific values for each month. However, a daily SWE index can be derived by a simple linear interpolation of the plot. As discussed, any one of the SNOTEL sites that are consider for the analysis, if exceeds the critical value, will be evaluated for the suspension with other criteria including reservoir level and soil moisture contents. It is recommended to compare all the SNOTEL stations used in this analysis to make the final suspension decision in a basin. In the case of a missing SNOTEL observation or limited SNOTEL observation, the ranking of SNOTEL stations that were derived from the regression results will help to set priorities.

Descriptive statistic (mean, standard, range, and 95% values) of the statewide suspension criteria is presented in the last six rows of Table2. The calculated average suspension criteria from this study are 230%, 197%, 183%, and 178% for January 1, February 1, March 1, and April 1, respectively. The 95th percentile of the mean value will reflect climatic and hydrologic variability in a basin. For example, atmospheric variability resulting from El Niño Southern Oscillation (ENSO) episodes and fluctuations of precipitation and hydrologic interactions. Most importantly, it will also capture the precipitation and streamflow variability due to localized factors including topography, geology, elevation, and natural land cover.

The question could be asked why other advanced statistical techniques, such as Principal Component Analysis (PCA), were not adopted if multi-collinearity exists among the SNOTEL stations. The PCA was performed prior to the regression analysis, and calculated results were satisfactory (not presented in this report). However, from the implementation point of the view, the PCA results would not be readily applicable when there are missing observations from the SNOTEL stations that were considered for this analysis. This means, for example, if there were four SNOTEL observations, and two of the station's observations were not available, the PCA index has to be reanalyzed before making the suspension decision. Moreover, the combined index generated by the PCA will be difficult to communicate and interpreted without the support of an expert. In addition, the predictors considered for this analysis were only SWE values that fit a simple regression model and are very easy to analyze and implement compared to the PCA and other similar techniques.

In this analysis, the critical flows were derived from the 95th percentile value. One may ask what will happen if the cloud seeding is done to only the 75th or 85th percentile of the seasonal mean values, or lower than the 95th percentile of the critical streamflow. As indicated, the justification for picking the 95th percentile of the critical streamflow is to augment the water supply to the highest possible level as the empirical results of cloud seeding show potential increment of the annual streamflow to be about 5%. Interestingly, in most of the basins the suspension years indicated from this analysis also roughly matching to years when the cloud seeding project were suspended. Clearly, the lower percentile will lower the SWE index to suspend cloud seeding – which means suspending the cloud seeding program earlier. This study does not include any sensitivity analysis to compare the SWE indices at different critical flow conditions (i.e., other than 95th percentile). Moreover, the level of cloud seeding will also depend on the costs required and budget available. Therefore, further analysis of the costs and performance target (increment to the runoff level) will help to select a specific critical flow level in a given basin or basins.

As presented, the magnitude of floods depends on various factors, including characteristics of precipitation (snowpack, proportion of rain and snow, intensity and duration of rainfall), contributing factors to snowmelt (air temperature, relative humidity, solar radiation, and wind speed), topographical features (area, slope, and soil type) and more. Often, extreme weather events or high intensity and short duration storm events are responsible for escalating peak flows or generating a flash flood event. The risk of flood also depends on vulnerability of flood-prone areas (e.g., exposure of infrastructure systems, settlements, agriculture, and other important resources). Therefore, a detailed analysis of flooding processes considering important factors and their interactions in a basin is beyond the scope of this study.

Table 3 presents a summary of flood categories and observed floods in the last 100 years extracted from the NWS website. The five flood categories (major flood stage to low stage) in the Logan basin at the Logan Station are classified based on flood stages ranging from 6.0 to 0.00 feet. The historical maximum flood stage observed at the same station was 7.50 feet in 1907. In addition, the historical flood events that exceeded the action stage (5.0 feet) were in 1983, 1984, and 1986.

The critical flow volume was compared with the historical flooding events in the river basins. For example, Figure 8 shows the plot of the historical seasonal, average, and critical flow volumes for the Logan basin at Logan Station. From the plot, it is clear that the flow volume exceeds the observed flow volume of 1984, 1986, 2011, and 2017. This means those four years are used to indicate when to suspend cloud seeding activities. Comparing the results of Figure 6 with Table 12, three years - 1984, 1986, and 2017 - are included as the flooding years. This means the 95th percentile critical streamflow level, as an indicator, has a likelihood of mitigating some of the extreme flooding events but that cannot be guaranteed due to the complexity of the flooding processes and associated risks.

Table 14 presents the flood categories, flood stages, and historical records for the Weber River near Plain City, Bear River near the Wyoming/Utah state line, and Sevier River near Hatch. The records show that the flood stages vary from basin to basin. It is evident that the observed floods are during the months of May and June except in the Sevier River basin, which also had flooding events in September and December. The historical high flooding events may be due to the contribution of snowmelt from the higher elevations in the basin; however, there is limited information available on the historical evaluations of precipitation, snow and rain ratios, seasonal variation of the stream flows, and other storm events in the year of the flood events. Therefore, it is difficult to confirm whether snowmelt was the main contributing factor for flooding in those years.

In conclusion, it is determined that: (1) the proposed SWE indices-based cloud suspension criteria derived from the critical flow as an indicator of potential April-July are easy to implement; (2) the critical flow will potentially ensure augmentation of water supply sources up to the 95th percentile of the historical records level; and (3) the SWE indices-based values are comparable to the current practices of cloud seeding SWE suspension criteria in Utah and will likely have the potential to exclude excessive snowmelt flooding events.

Table 14. *Flood categories and historical records of flooding at the Logan River near Logan, Weber River near Plain City, Bear River near the Wyoming/Utah state line, and Sevier River near Hatch (Source: NWS, 2018).*

Basin	Flood Categories	Flood stage (in feet)	Example of flood stage (in feet) and historical critical record date
1) Logan at Logan	Major flood	6.00	7.50 ft on 05/24/1907, 6.50 ft on 05/31/1984, 5.80 ft on 05/31/1983, 5.70 ft on 05/31/1986, 4.90 ft on 05/24/2005, 4.40 ft on 06/07/2010, 3.70 ft on 05/03/2007.
	Moderate flood	5.50	
	Flood stage	5.00	
	Action stage	5.00	
	Low stage	0.00	
2) Weber River near Plain City	Major flood	29.00	24.70ft on 04/18/2006, 24.18 ft on 5/03/1999, 24.10 ft on 05/12/2005, 24.00 ft on 05/11/1985, 23.82 ft on 06/10/1995, 23.32 ft on 06/20/1998, 23.13 ft on 05/07/1993.
	Moderate flood	28.00	
	Flood stage	27.00	
	Action stage	25.00	
	Low stage	0.00	
3) Bear River near Wyoming/Utah state line	Major flood	9.50	7.82 ft on 06/30/2011 7.72 ft on 6/08/2010 7.70 ft on 06/09/2017 7.40 ft on 06/09/2014 7.40 ft on 06/09/2016 7.06 ft on 06/15/1995 7.05 ft on 06/11/1990 7.04 ft on 05/30/2014.
	Moderate flood	9.00	
	Flood stage	8.00	
	Action stage	7.00	
	Low stage	0.00	
4) Sevier River near Hatch	Major flood	4.70	5.11 ft on 12/25/1971 4.36 ft on 06/02/1983 4.11 ft on 09/01/1931 3.98 ft on 05/17/1993 3.80 ft on 05/24/1980
	Moderate flood	4.30	
	Flood stage	3.90	
	Action stage	3.50	
	Low stage	0.00	

The SWE indices results presented for each of the basins will be used to suspend cloud seeding project/activities. However, a final suspension decision should be made after a thorough assessment of other important factors including: (1) extreme weather conditions (cloud seeding will be suspended if there is a warning of extreme avalanche danger, the possibility of considerable rain at higher elevations that might lead to local flooding, potential flood conditions that may exist in or around any of the project areas, or flash flood warnings); (2) amount of precipitation in prior seasons, soil moisture conditions in the basin, reservoir storage level, and stream flow forecasts; and (3) potential increased risks of flooding due to forest fires.

4.2 Recommendations

This study presented the results of the cloud seeding suspension criteria based on the observed SNOTEL observations and seasonal critical flows. It is known that cloud seeding is a complex process and its effectiveness depends not only on meteorological and hydrologic factors, but also varies from unknown micro-components of the complex microphysical properties of atmospheric and land interactions, as well as cloud properties. Interactions of predominant climate and catchment factors and processes govern changes in regional hydrology. Increasing winter temperature, reduced snowpack, and early snowmelt will have effects on future streamflow and water availability. Therefore, future suspension decisions should be made considering the interdisciplinary analysis of the soil moisture level, observed seasonal streamflow, forecasted stream flows, reservoir levels, extreme weather forecasts of potential flooding, and forecasted seasonal streamflows.

Despite ongoing substantial research and advancement in cloud seeding science, there are no publications (based on the web search) that present a scientific method to select a set of cloud seeding suspension indicators that can be replicated in this study. Moreover, there are very few publications reported to assess the performance of cloud seeding. It is recommended that future studies be done to simulate streamflows in the basin using a hydrologic model (a physically based model that also addresses snowmelt) and a new Snowmelt Tracking Algorithm. There are also opportunities to apply Machine Learning Algorithms (e.g., support vector machine considering the SNOTEL, precipitation, streamflows, reservoir levels, soil moisture contents, etc.) in the future, along with data availability and advancement in data analytics. Similarly, assessment of cloud seeding performances using a very high-resolution climatic model (such as the WRF model developed by NCAR) will be helpful in addressing changing snowpack, snowmelt, and timing of the streamflow as long as such models have been verified by independent observations.

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Appendices

Table 1A. *Results of the linear regression between the SWE values observed on Jan 1st, Feb 1st, March 1st, and April 1st at the three SNOTEL stations and the 95th percentile of cumulative volume of the seasonal streamflows at the Logan Station.*

<table>
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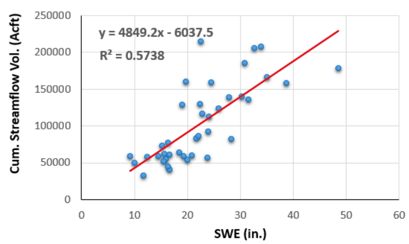
<td>
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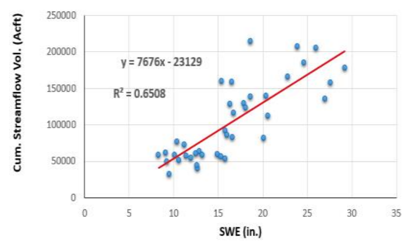
<td>
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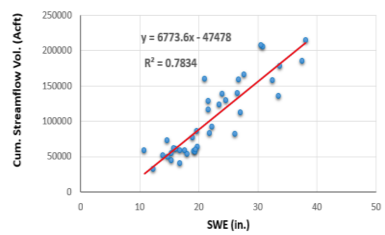
<td>
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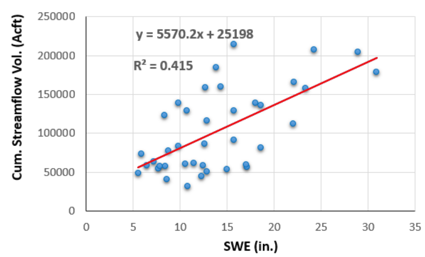
<td>
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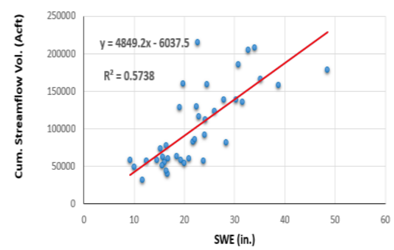
<td>
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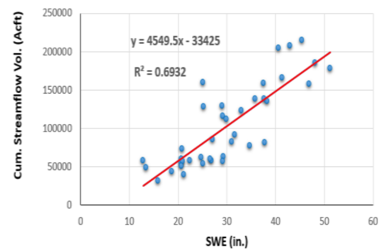
<td>
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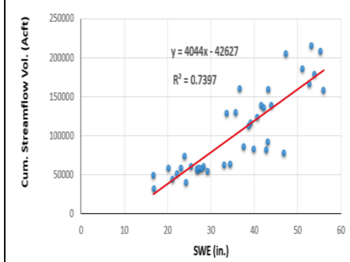
<td>
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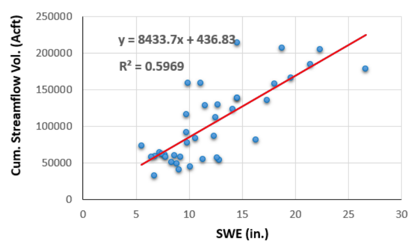
<td>
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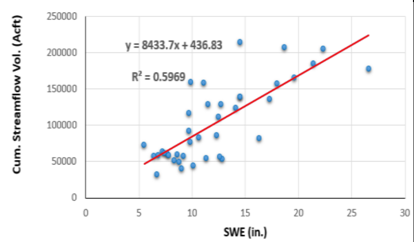
<td>
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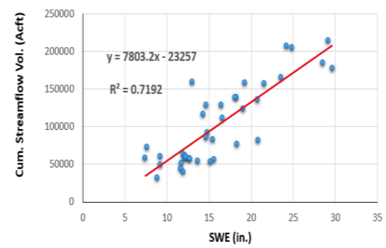
<td>
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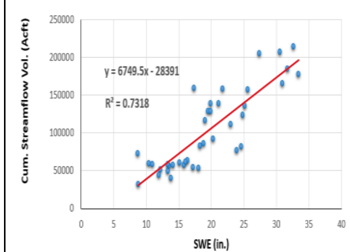
<td>
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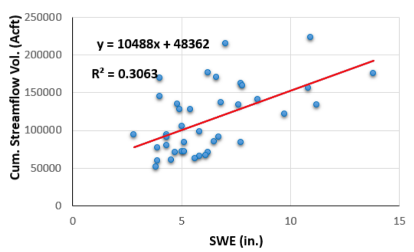
Table 2A. *Results of the linear regression between the SWE values observed in Jan 1st, Feb 1st, March 1st and April 1st at the four SNOTEL stations and the 95th percentile of cumulative volume of the seasonal streamflows at the Weber Basin near Oakley.*

<table>
<tr><th>SNOTEL stations</th><th>Jan 1st</th><th>Feb 1st</th><th>March 1st</th><th>April 1st</th></tr>
<tr><td>Hayden Fork</td>
<td>
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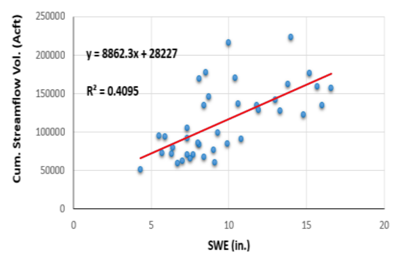
<td>
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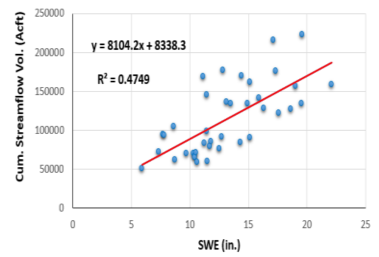
<td>
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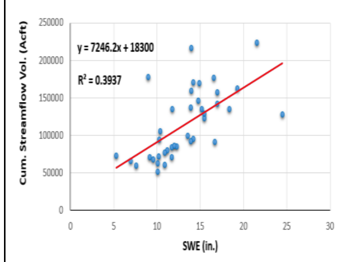
<td>
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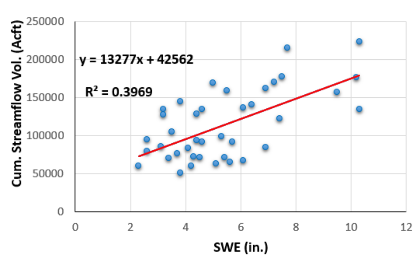
<td>
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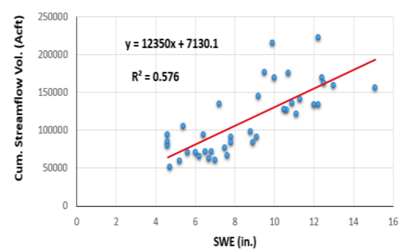
<td>
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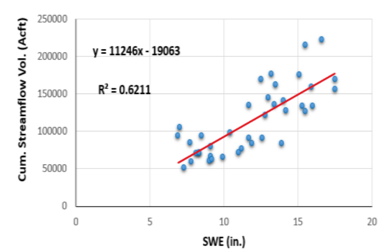
<td>
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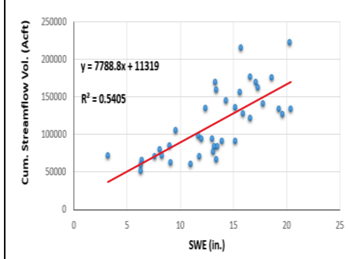
<td>
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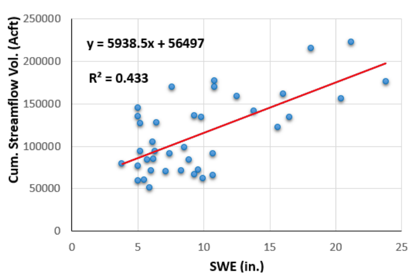
<td>
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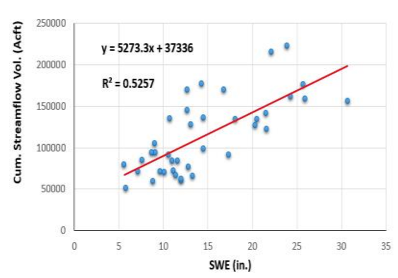
<td>
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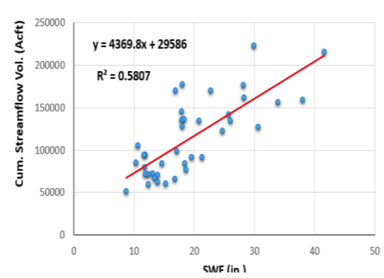
<td>
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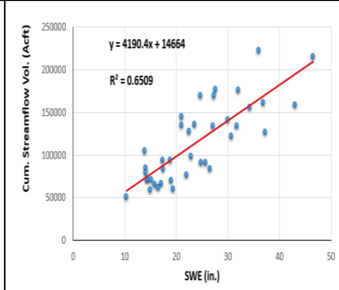
<td>
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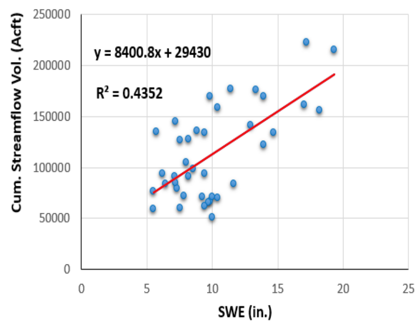
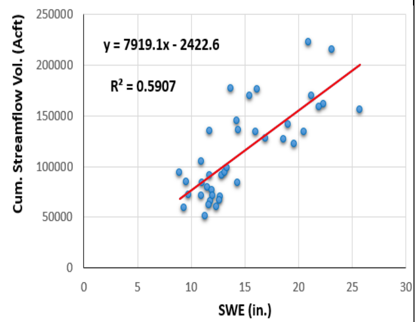
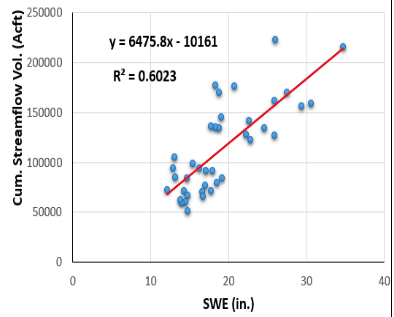
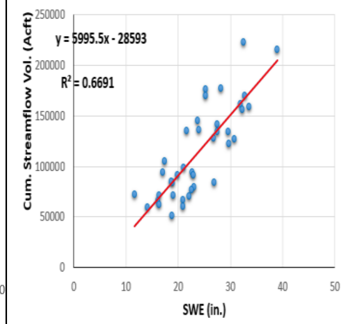
Chalk Creek	 y = 8400.8x + 29430 R² = 0.4352 Cum. Streamflow Vol. (Acft) SWE (in.)	 y = 7919.1x - 2422.6 R² = 0.5907 Cum. Streamflow Vol. (Acft) SWE (in.)	 y = 6475.8x - 10161 R² = 0.6023 Cum. Streamflow Vol. (Acft) SWE (in.)	 y = 5995.5x - 28593 R² = 0.6691 Cum. Streamflow Vol. (Acft) SWE (in.)

Table 3A. *Results of the linear regression between the SWE values observed in Jan 1st, Feb 1st, March 1st and April 1st at the two SNOTEL stations and the 95th percentile of cumulative volume of the seasonal streamflows at the Dunn Creek Basin near Park Valley.*

<table>
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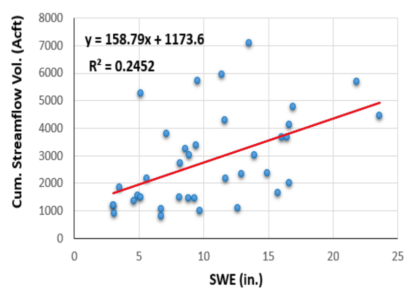
<td>
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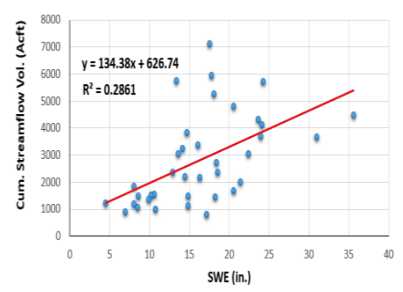
<td>
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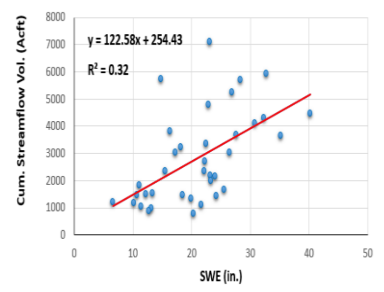
<td>
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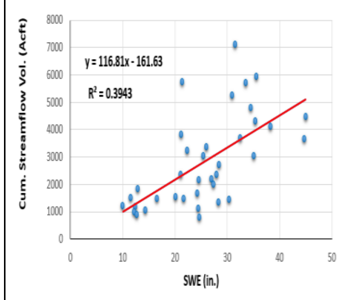
<td>
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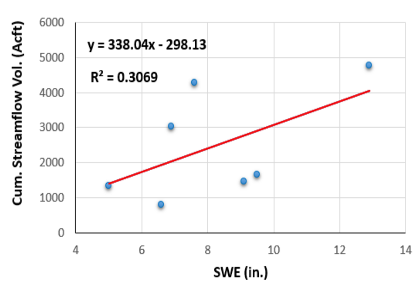
<td>
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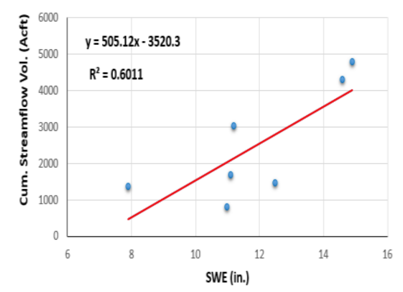
<td>
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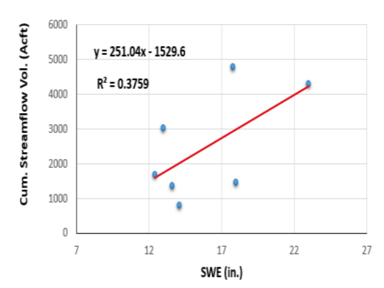
<td>
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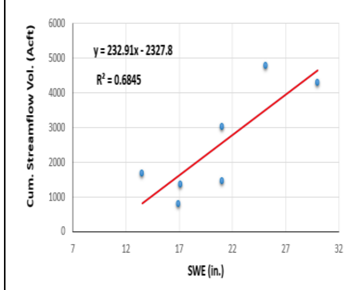
<td>
</td></tr>
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Table 4A. *Results of the linear regression between the SWE values observed in Jan 1st, Feb 1st, March 1st and April 1st at the three SNOTEL stations and the 95th percentile of cumulative volume of the seasonal streamflows from the Sevier River Basin at Hatch.*

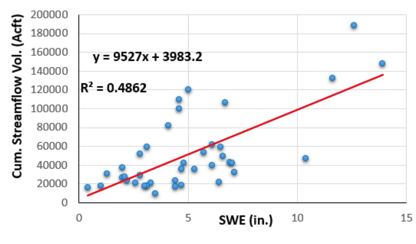
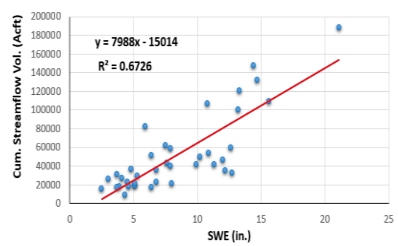
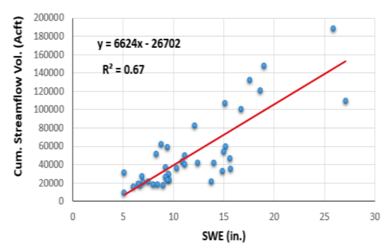
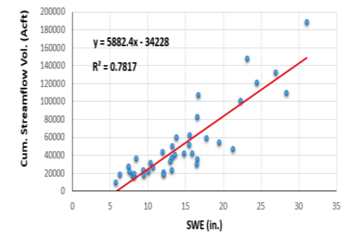
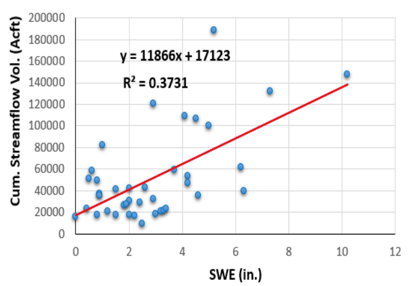
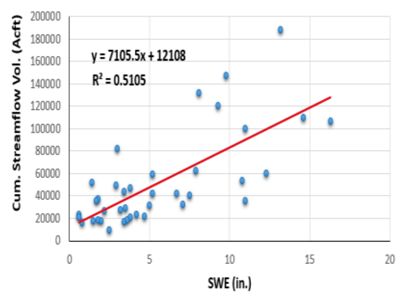
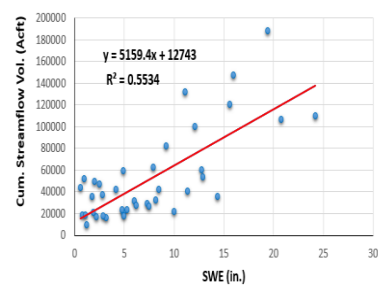
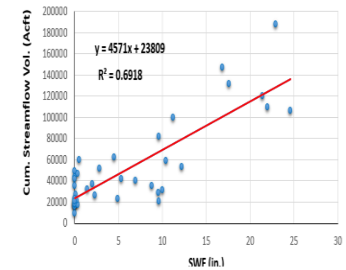
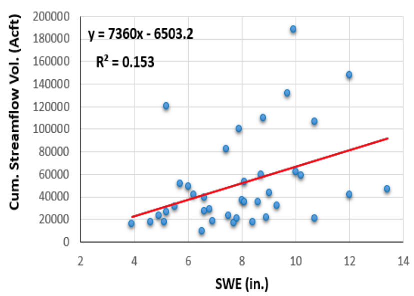
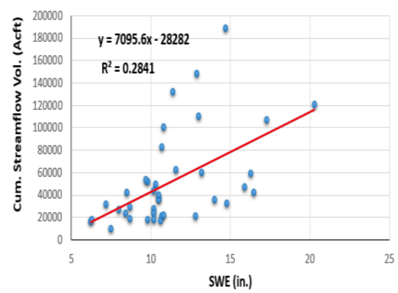
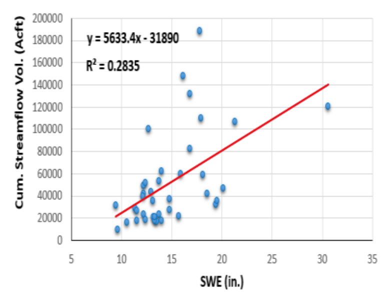
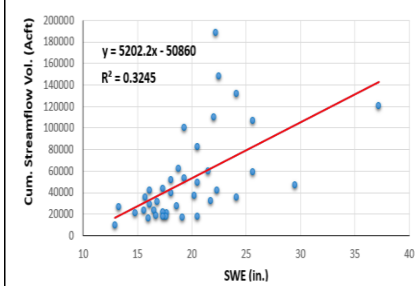
<table>
<tr><th>SNOTEL stations</th><th>Jan 1st</th><th>Feb 1st</th><th>March 1st</th><th>April 1st</th></tr>
<tr><td>1. Castle Valley</td>
<td></td>
<td></td>
<td></td>
<td></td></tr>
<tr><td>2. Harris Flat</td>
<td></td>
<td></td>
<td></td>
<td></td></tr>
<tr><td>3. Farnsworth Lake</td>
<td></td>
<td></td>
<td></td>
<td></td></tr>
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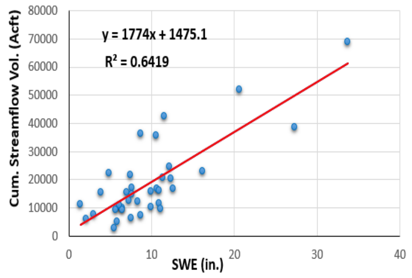
Table 5A. *Results of the linear regression between the SWE values observed on Jan 1st, Feb 1st, March 1st and April 1st at the two SNOTEL stations and the 95th percentile of cumulative volume of the seasonal streamflows in Coal Creek Basin near Cedar City*

<table>
<tr><th>SNOTEL stations</th><th>Jan 1st</th><th>Feb 1st</th><th>March 1st</th><th>April 1st</th></tr>
<tr><td>1. Midway Valley</td>
<td>
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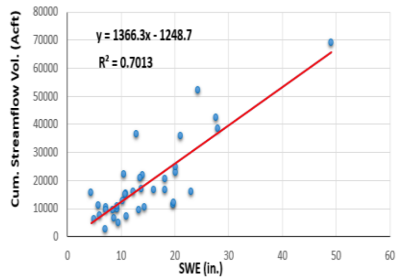
<td>
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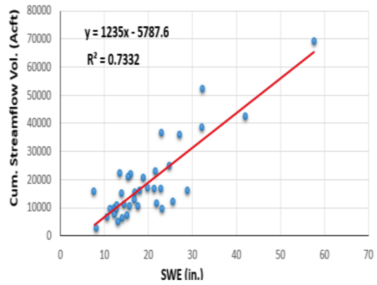
<td>
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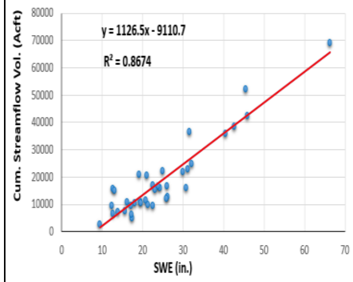
<td>
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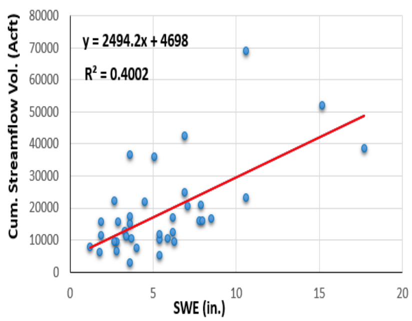
<tr><td>2. Webster Flat</td>
<td>
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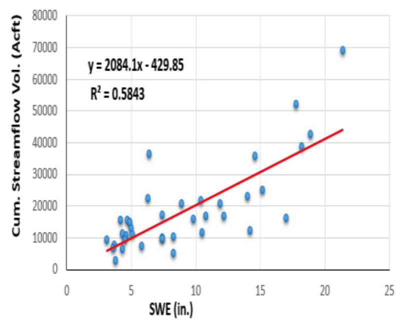
<td>
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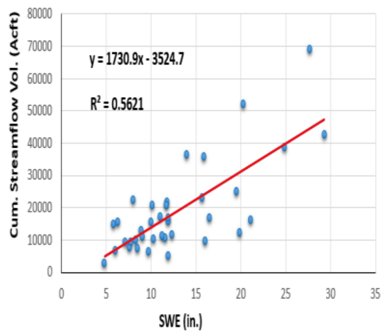
<td>
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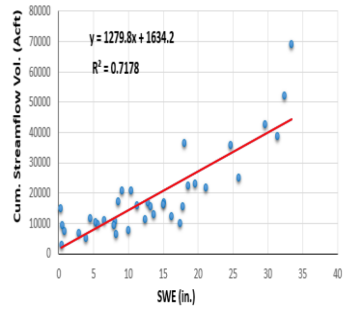
<td>
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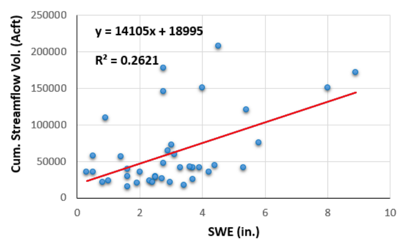
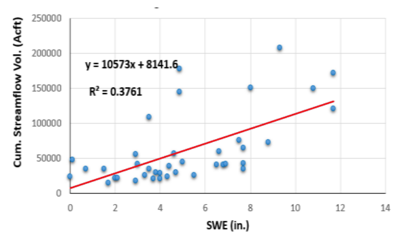
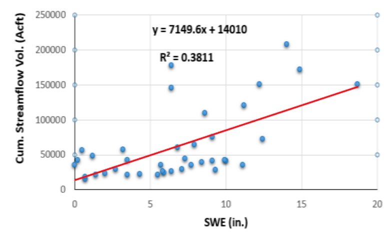
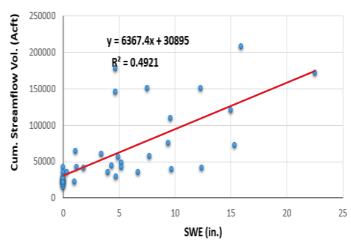
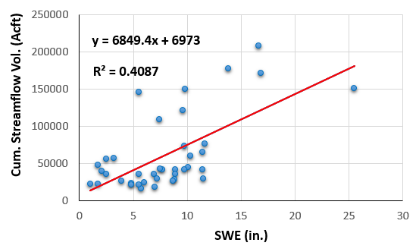
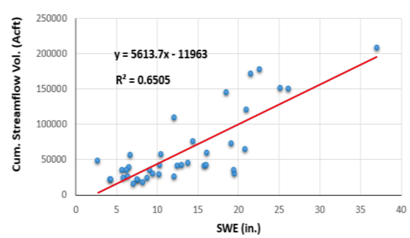
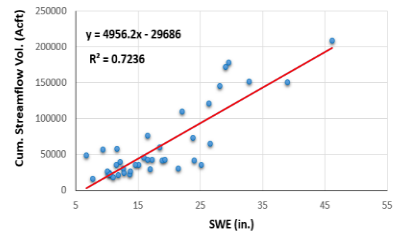
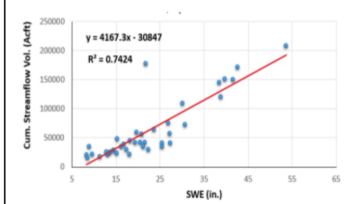
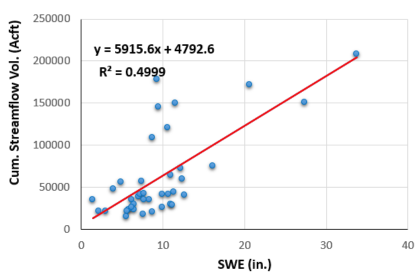
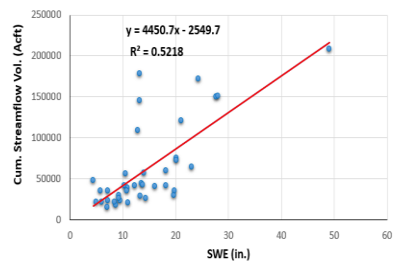
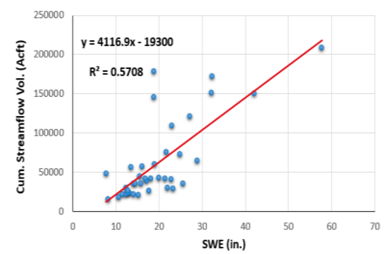
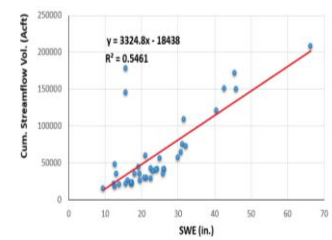
Table 6A. *Results of the linear regression between the SWE values observed on Jan 1st, Feb 1st, March 1st and April 1st at the four SNOTEL stations and the 95th percentile of cumulative volume of the seasonal streamflows in Virgin River Basin at Virgin.*

SNOTEL stations	Jan 1st	Feb 1st	March 1st	April 1st
Long Flat				
Kolob				
Midway Valley				

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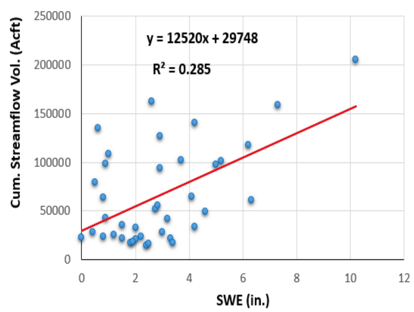
<td>
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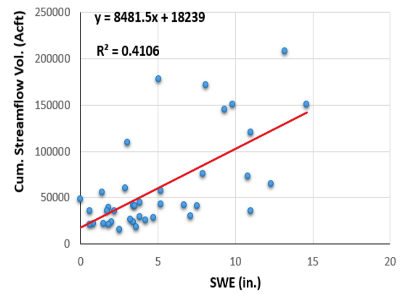
<td>
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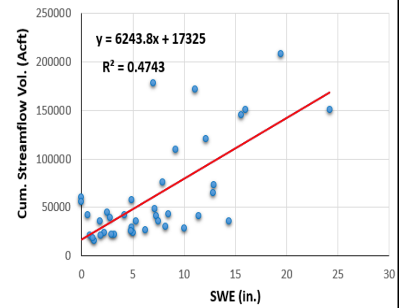
<td>
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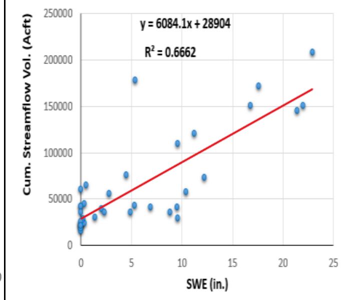
<td>
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</tr>
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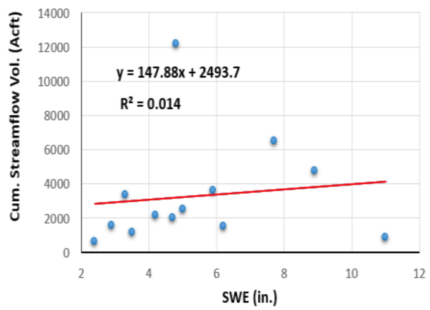
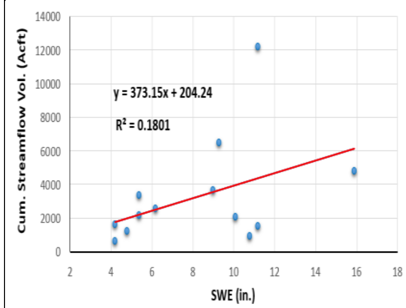
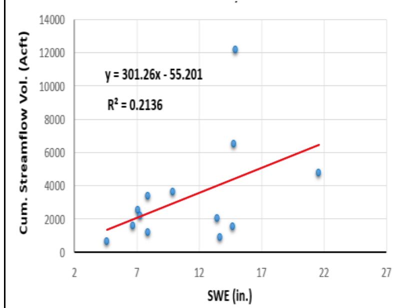
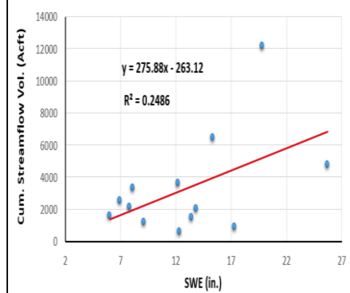
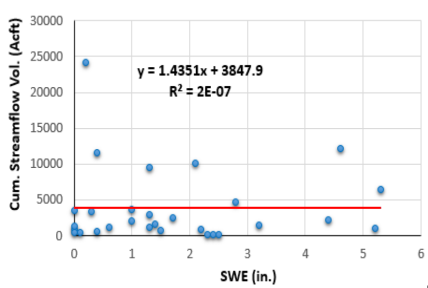
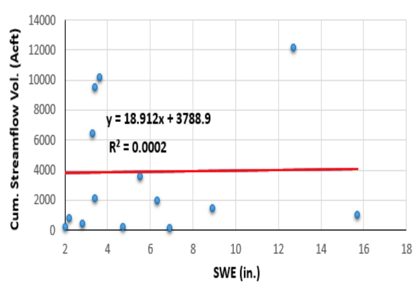
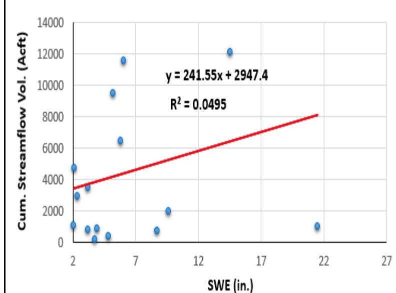
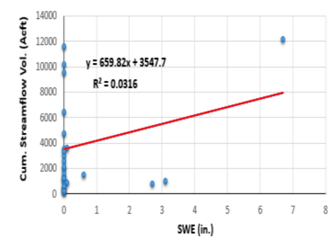
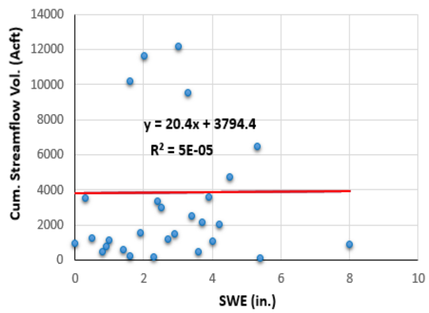
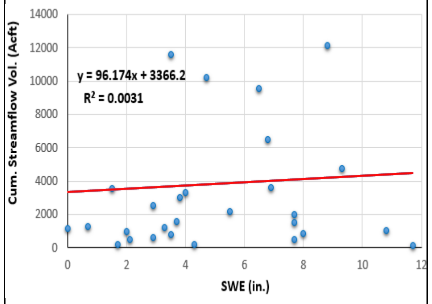
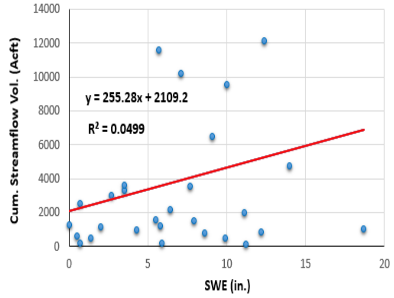
Table 7A. *Results of the linear regression between the SWE values observed on Jan 1st, Feb 1st, March 1st and April 1st at the two SNOTEL stations and the 95th percentile of cumulative volume of the seasonal streamflows in the Santa Clara River Basin above Baker Reservoir.*

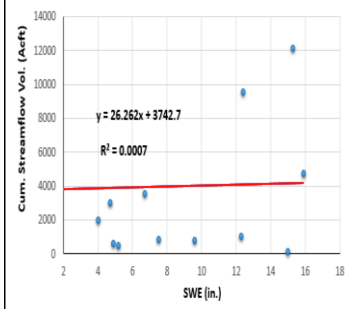
SNOTEL stations	Jan 1st	Feb 1st	March 1st	April 1st
1. Gardner Peak				
2. Little Grassy				

3. Long Flat

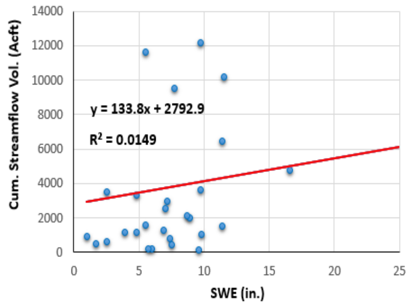


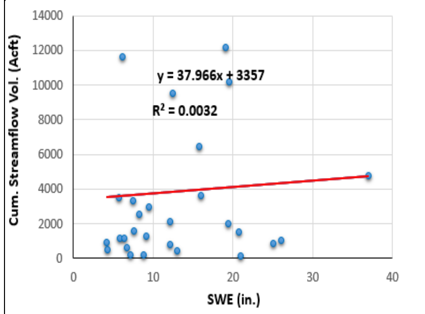


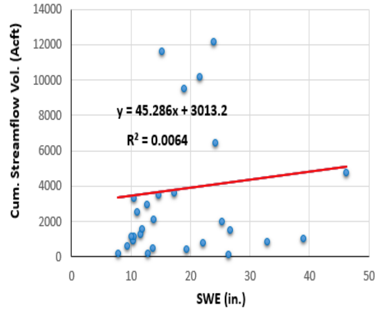




4. Kolob







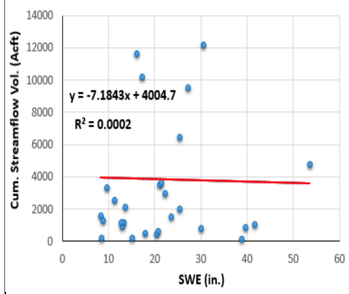


Table 8A. *Results of the linear regression between the SWE values observed on Jan 1st, Feb 1st, March 1st and April 1st at the two SNOTEL stations and the 95th percentile of cumulative volume of the seasonal streamflows for the South Willow Creek Basin near Grantsville.*

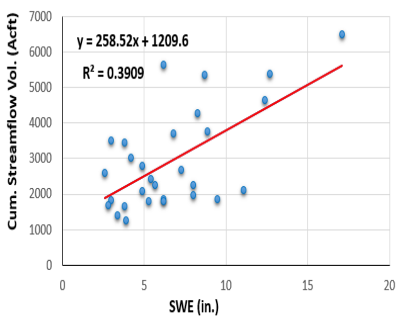
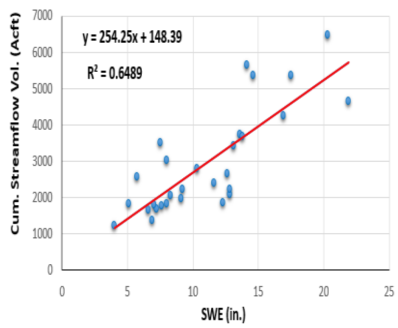
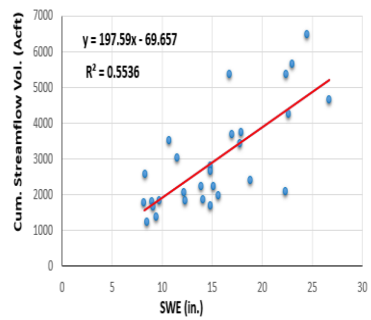
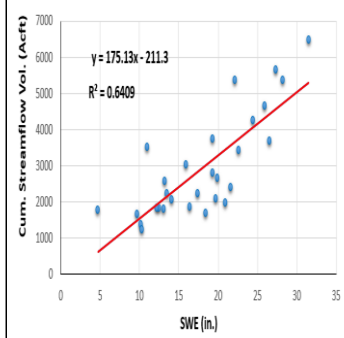
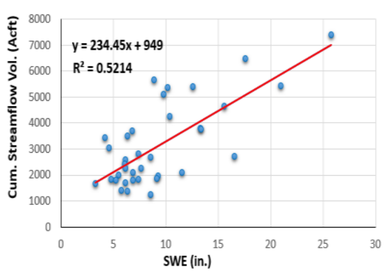
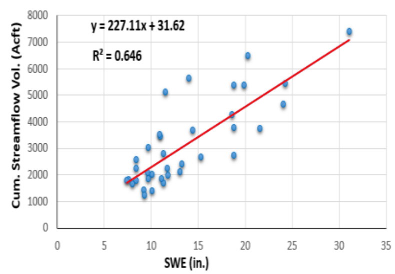
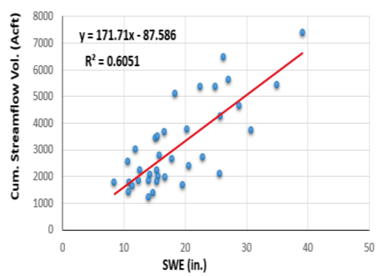
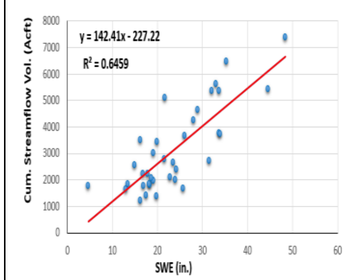
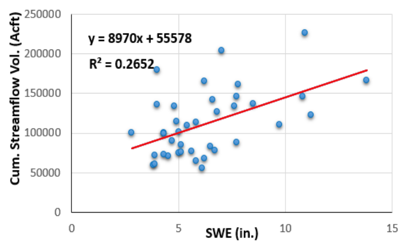
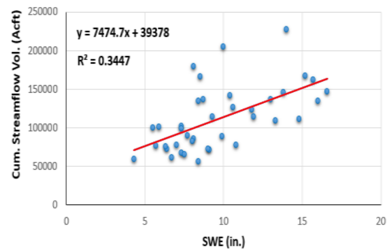
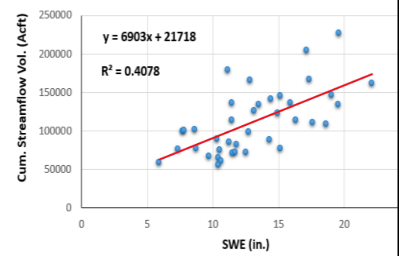
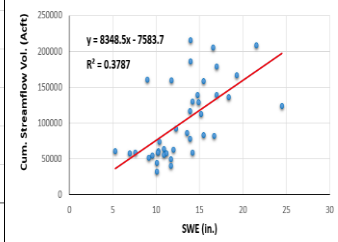
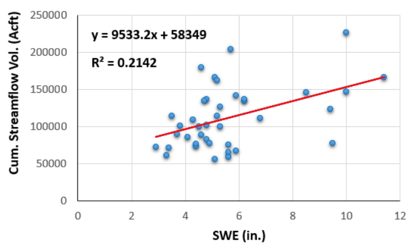
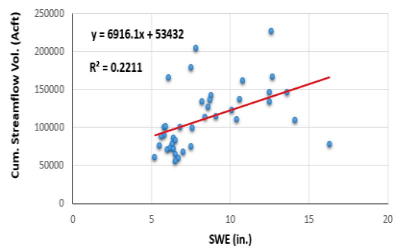
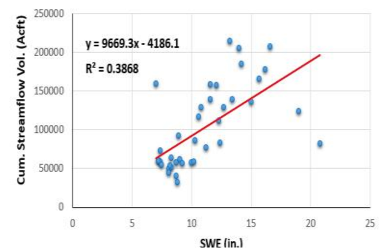
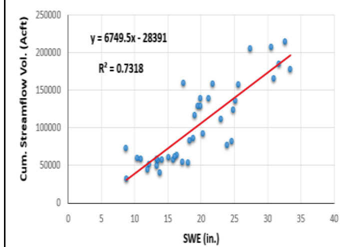
SNOTEL stations	Jan 1st	Feb 1st	March 1st	April 1st
1. Mining Fork				
2. Rocky Basin-Settlement				

Table 9A. *Results of the linear regression between the SWE values observed on Jan 1st, Feb 1st, March 1st and April 1st at the three SNOTEL stations and the 95th percentile of cumulative volume of the seasonal stream flows for the Bear River near Utah/Wyoming state line.*

SNOTEL stations	Jan 1st	Feb 1st	March 1st	April 1st
1. Hayden Fork				
2. Lily Lake				

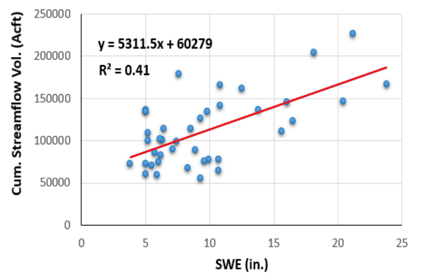
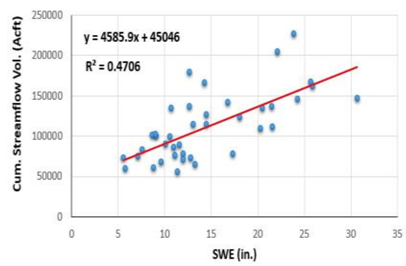
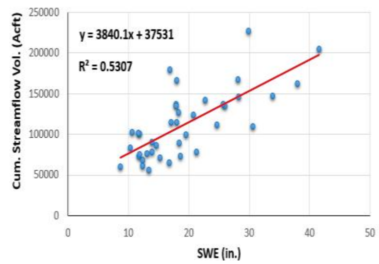
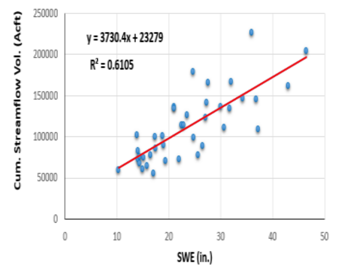
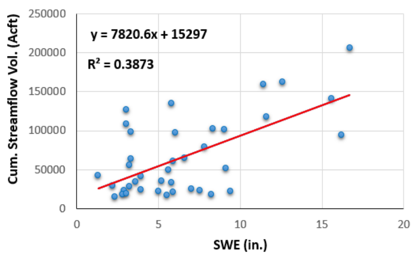
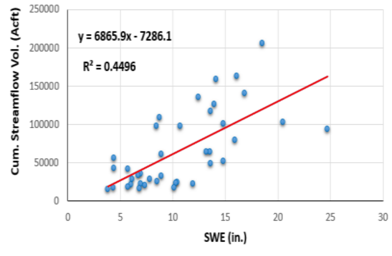
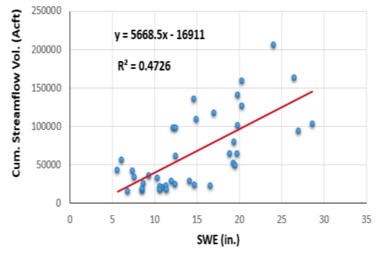
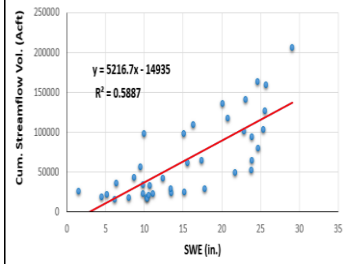
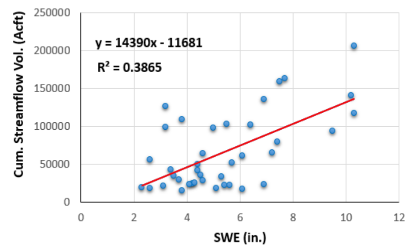
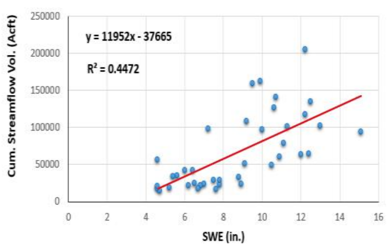
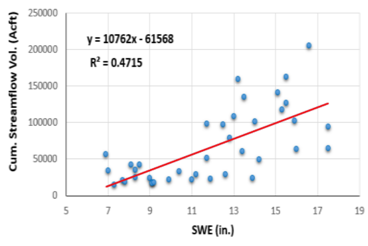
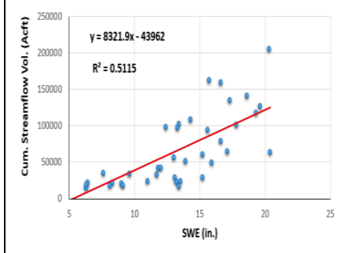
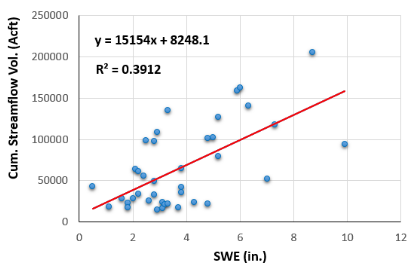
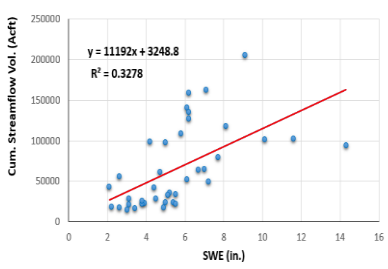
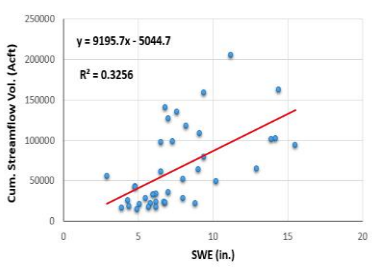
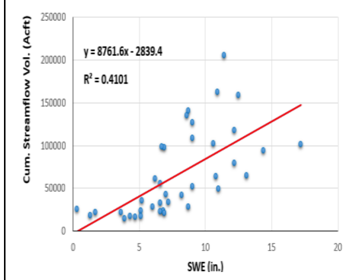
3. Trial Lake	y = 5311.5x + 60279 R² = 0.41 Cum. Streamflow Vol. (Acft) SWE (in.)	y = 4585.9x + 45046 R² = 0.4706 Cum. Streamflow Vol. (Acft) SWE (in.)	y = 3840.1x + 37531 R² = 0.5307 Cum. Streamflow Vol. (Acft) SWE (in.)	y = 3730.4x + 23279 R² = 0.6105 Cum. Streamflow Vol. (Acft) SWE (in.)

Table 10A. *Results of the linear regression between the SWE values observed on Jan 1st, Feb 1st, March 1st and April 1st at the four SNOTEL stations and the 95th percentile of cumulative volume of the seasonal streamflows for the Duchesne River Basin.*

SNOTEL stations	Jan 1st	Feb 1st	March 1st	April 1st
1. Daniels-Strawberry				
2.Smith Morehouse				
3.Rock Creek				

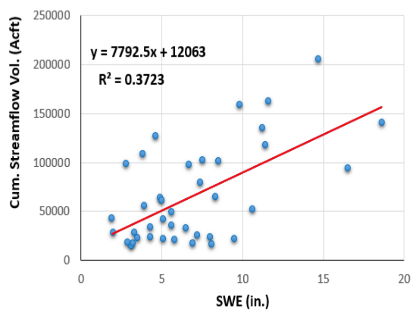
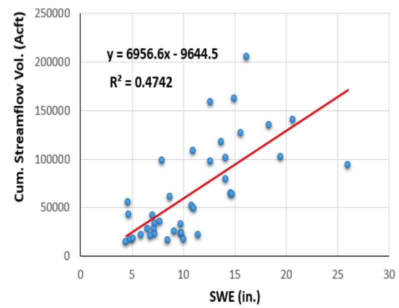
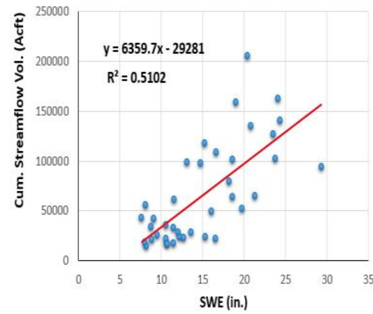
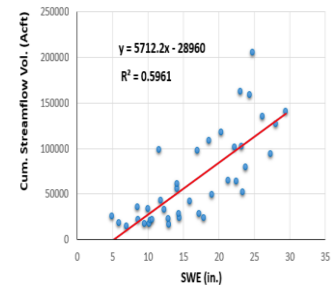
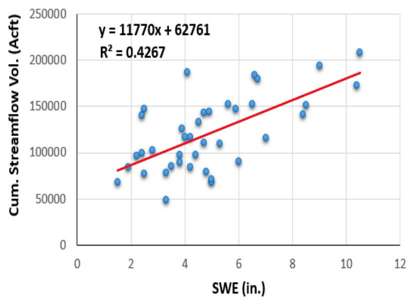
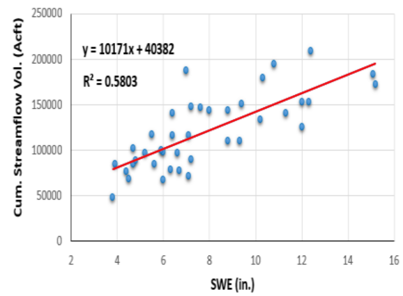
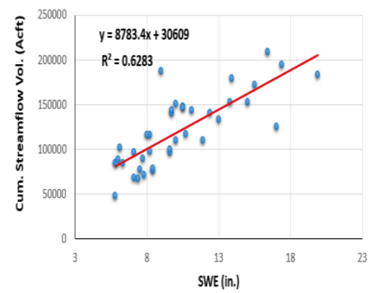
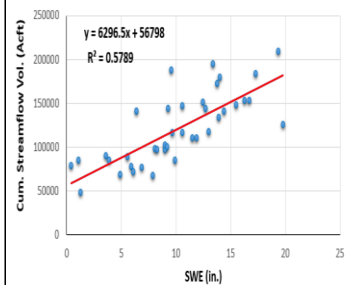
4.Strawberry Divide				

Table 11A. *Results of the linear regression between the SWE values observed on Jan 1st, Feb 1st, March 1st and April 1st at the two SNOTEL stations and the 95th percentile of cumulative volume of the seasonal streamflows at the Provo River near Woodland.*

SNOTEL stations	Jan 1st	Feb 1st	March 1st	April 1st
1. Beaver Divide				
2.Trial Lake