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Modeled streamflow response under cloud seeding in the North Platte River watershed

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ABSTRACT

Severe and more persistent droughts in the arid regions such as the western US have increased the interest in cloud seeding programs or weather modification (WM) operations to increase precipitation. An anticipated increase in precipitation could augment annual and seasonal streamflow and reduce the impacts during dry periods. This paper evaluates hydrological impacts of WM operations in the North Platte River watershed, by utilizing a hydrologic model. The Variable Infiltration Capacity (VIC) land surface hydrological model is calibrated and validated for the periods of 1950–80 and 1981–2000 respectively, using daily meteorological forcing and monthly streamflow data. Two sets of WM scenarios are developed and forced into the VIC model to quantify the impacts of increased precipitation on streamflow. The first scenario is based on existing WM operations in the State of Wyoming. The second scenario hypothetically apply WM throughout the watershed to identify suitable regions for cloud seeding operations. For the first scenario, an increase of 0.3–1.5% in annual streamflow is observed from model simulations for a 1–5% increase in precipitation. Follow-on scenarios have identified the central-west and south-west regions of the watershed, which consist of a higher coverage of Evergreen Needleleaf Forest, to generate higher streamflow during WM operations. The north-east and north-west regions, which consist of a higher coverage of open shrublands and grasslands, are found to generate lower increases in streamflow during these operations. The observed annual precipitation is higher for central and southern regions when compared to northern regions of the watershed. It can be considered that the simulated changes in streamflow from different regions could also be attributed to variation in annual precipitation distribution within the watershed rather than solely based on cloud seeding operations. For the proposed WM programs or programs that are claimed effective based on precipitation augmentation, the hydrological impacts can be evaluated based on this analysis.

1. Introduction

Snowpack augmentation and runoff enhancement are considered to be an integral part of regional water management in many arid and semi-arid regions. An increase of droughts in arid regions such as the western US has necessitated cloud seeding programs or herein referred to as weather modification (WM) programs. The major goal of WM programs is to prevent water shortage, reduce the impact of drought, and enhance reservoir storage with augmented water supply.

Wintertime cloud seeding is considered scientifically most efficient and credible for larger scale WM programs (Hunter, 2007). A properly designed and implemented WM program could increase snowpack in the range of 5–15% (AMS, 1998; WMA, 2005). Studies have identified an increase of 6% in agricultural wheat production and a decrease in crop hail loss of 45% in North Dakota (Smith et al., 1992, 1997). An increase in snowpack of about 7% and a higher reservoir level has been observed in the operational cloud seeding project in the Upper Snake River Basin, Idaho (Barker, 2009). The amount of precipitation was more than doubled in a silver iodide based cloud seeding project in Texas (Rosenfeld and Woodley, 1989). WM programs that were implemented and evaluated in different regions have shown positive feedback for precipitation enhancement in most cases (e.g. Ryan et al., 2005; Huggins, 2007;Woodley and Rosenfeld, 2008; Griffith et al., 2009). WM programs are considered to be 'cost effective and environmental friendly' technology (WWDC, 2005). The production of additional water supply through cloud seeding is considered inexpensive compared to building new infrastructures (Grant, 1983; Breed, 2008). KWO (2001) estimated the cost in the range of $0.8–12 per 1000 cubic meters ($1–15 per acre foot, AF) of additional runoff from snowpack in Kansas. Utah Department of Natural Resources (2005) has estimated the cost to be approximately $1.6 per cubic

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meters ($2.0 per AF) of additional runoff for the combined projects in Utah.

WM programs are claimed effective with an increase in precipitation in the range of 5–20%. Verifying the effects of cloud seeding is difficult; however, WM programs are justified based on cost vs. probabilistic benefit analysis (NRC, 2003). The recorded benefit cost ratio, which also includes the applications of increased runoff from the WM projects, ranges from 20 to 40 for most of the WM projects (e.g. Sell and Leistritz, 1998; Stauffer and Williams, 2000;ASCE, 2006). With increasing water demand, WM projects are expected to increase in different water stressed parts of the world.

WM programs have been operating in most of the western US since the 1950s to fulfill the increasing water demand in these regions. Reconstructed climate data has indicated the occurrence of very lengthy and severe droughts in the arid western US in the past (USGS, 2004). The Colorado River Basin, a major source of water supply for the western US, has been in a drought since 1999 (BOR, 2006). Snowmelt runoff is the major source of water supply in the western US but a significant decrease in the mountain snowpack has been noticed in the last century in these regions (Mote et al., 2005). In California, there is a need of at least 2500 million cubic meters (2 million AF) of additional water to sustain the urban growth by 2030 (Shaw, 2006). The United States Department of Interior (US DoI, 2003) has also reported the continuous increase in the consumptive use of water in the West to sustain urban growth. It could create serious water conflicts in the future while meeting the higher water demand. In addition, decreased snowpack runoff could impact production of hydroelectric power, thus creating adverse impacts on the power demand of California and other western States (Griffith and Solak, 2006; Hunter, 2007). The trend of increasing water demand and declining snowpack could worsen the situation even more if no significant action is taken (US DoI, 2003). WM programs have been considered the most attractive option for increasing water availability.

Since 1972, the glaciogenic seeding of winter orographic clouds has been ongoing in the headwater watersheds of the Colorado River Basin (Cotton, 2007). Cloud seeding is estimated to contribute from 980 to 2220 million cubic meters (0.8–1.8 million AF) of water for the Colorado River Basin, which could result in a favorable benefit cost ratio for the program (Griffith and Solak, 2006). The feasibility study of operational cloud seeding program in the Salt River and the mountains of Wyoming have shown an average increase of 10% in the November through March precipitation (Griffith et al., 2007). The Wyoming Water Development Commission (WWDC) through the Wyoming Weather Modification Pilot Project (WYMPP) has conducted silver iodide based cloud seeding during the winter period (60–80 days) for the months of November through April (WWDC, 2005). Most of the cloud seeding for the WYMPP is done in the North Platte River watershed (Sierra Madre and Medicine Bow ranges) in south central Wyoming and Wind Range River in west central Wyoming. WWDC initiated the program in spring 2005, and full scale cloud seeding operations started in 2007–2008. The present available water resources in the Platte River basin in Wyoming are fully allocated (WWDC, online accessed 2010). Under a moderate population growth, the water demand in the Green River Basin is expected to increase from 73% to 82% of its allocation given in the Colorado River and up to 88% in the Wind River (Big Horn) Basin. WWDC (2010) has estimated an additional 160–320 million cubic meters (130,000–260,000 AF) of water each spring from a 10% increase in precipitation from the proposed pilot projects. However, there is a need to further evaluate this increase in precipitation and quantify the impacts on water supply.

Most WM programs consider only the precipitation augmentation and do not quantitatively evaluate the significant hydrological impacts. Some past studies have utilized observed data to evaluate the hydrological impacts of WM, but they are limited and insufficient to account for uncertainties attributed to natural variability of rainfall and runoff in WM programs. The observed results may or may not be the results from the WM programs alone. Hydrological modeling is considered appropriate since various WM scenarios can be forced into the model that could consider uncertainties about the effects of these programs (Seely and DeCoursey, 1975). A physically based hydrologic model that operates at a higher resolution could provide more realistic simulations and account for complex topography and diverse climate of the western United States. This paper aims to evaluate the possible impacts of weather modification on water supply by utilizing a process based hydrologic model. The WM programs are expected to augment precipitation by 5% in the North Platte watershed. Through modeling and WM scenario analysis, this paper provides a quantitative assessment of change in water supply (streamflow) as a result of transformation of increased precipitation in the watershed. Since no studies related to hydrologic impact evaluation are yet done in the watershed, the impact on streamflow due to operational WM programs can be utilized for future water supply and demand management study.

2. Methodology

2.1. Study area

The study area is the North Platte River watershed which is located in the states of Wyoming and Colorado at latitude 40.3125° to 41.9375° N, and longitude 105.9375° to 107.0625° W (Fig. 1). The annual precipitation varies from 60 to 150 cm (25–60 in.) with 40–70% as winter snow. The watershed contains six streamflow gauges and eight SNOTEL stations, which are operated by United States Geological Survey (USGS) and Natural Resource Conservation Service (NRCS) respectively. The North Platte River, which is a tributary of the Platte River and starts at the high basin of North Park in north-central Colorado, flows northward into Wyoming along the Westside of Medicine Bow ranges and finally meets the Medicine Bow River and Seminoe Reservoir. The Platte River is a tributary of the Missouri River which is a tributary of the Mississippi River. The major sites of cloud seeding include the Sierra Madre and Medicine Bow ranges in south central Wyoming. On average, there are approximately 250 precipitation events expected in the target areas to attain a 10–15% increase in precipitation due to cloud seeding operations (Breed, 2008). These operations are conducted only in the Wyoming ranges of the North Platte River watershed. In the current research, the WM operations simulated in the Colorado ranges of the North Platte River watershed are hypothetical and are designed to provide insight on optimizing target areas for WM. Wyoming ranges represent the runoff sources from the Wyoming area of the North Platte River watershed. Colorado ranges represent the watershed area that lies in the Colorado and upriver of Wyoming.

2.2. Hydrologic model

The hydrologic model used in this analysis is the Variable Infiltration Capacity (VIC) model (Liang et al., 1994; Cherkauer and Lettenmaier, 2003). VIC is a macro-scale land surface semi-distributed hydrologic model which has been used in a variety of water resource applications and climate change studies (e.g. Pierce et al., 2008; Hidalgo et al., 2009). The model uses 1/8° gridded meteorological forcing data (precipitation, max and min temperature, wind speed), land cover, soil, elevation bands and other watershed characteristics to estimate surface water and baseflow. Simulations are carried out for each grid cell and the time series of output vari-

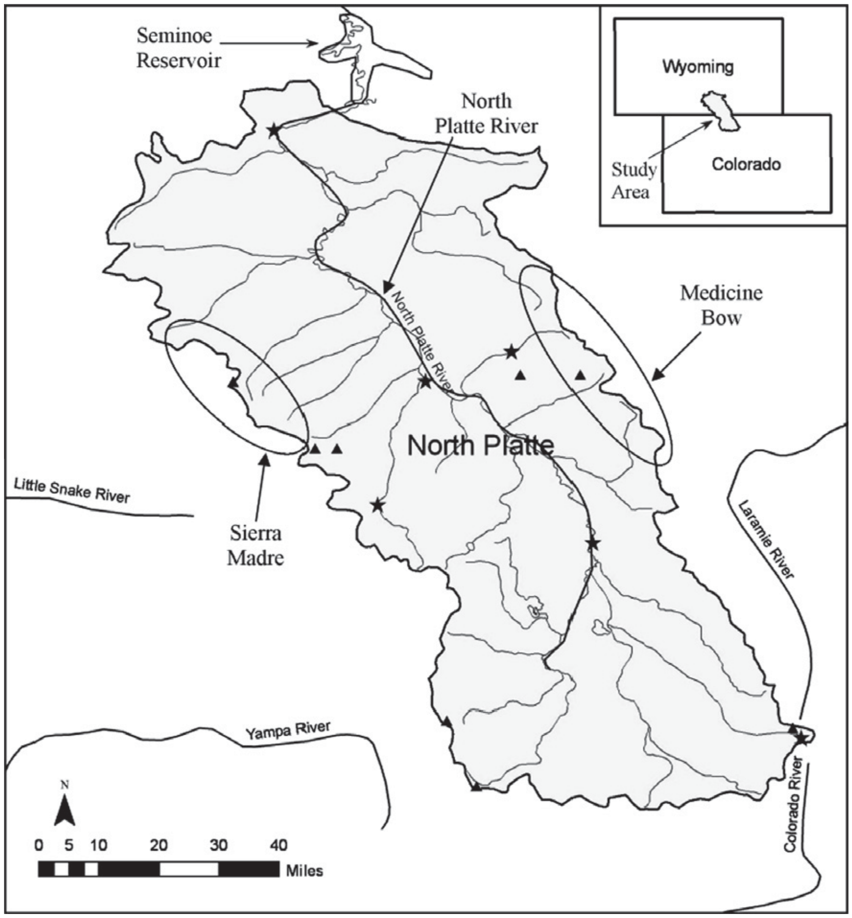

Fig. 1. Location of the North Platte River watershed, major areas for cloud seeding operations, and rivers, streamflow gauges (indicated by stars) and SNOTEL stations (indicated by triangles) located inside the watershed.

ables (e.g. runoff, soil moisture, snow water equivalent) are also stored separately for each grid. Simulations are carried out at daily or sub-daily time steps based on the two modes of operation-water balance and energy balance. Water balance mode considers equal temperature for soil surface and air, and it does not solve the surface energy balance. Energy balance mode solves the total water balance and simulates surface energy fluxes to compensate incoming total radiation fluxes. The surface fluxes include sensible heat, latent heat, ground heat, ground heat storage, and outgoing long wave.

The VIC model uses a separate river routing model of Lohmann et al. (1996) for the routing of streamflow. Various options exist during the VIC simulation, most of which are set in a 'global parameter file'. Newer versions of the VIC model include a snow algorithm that solves the surface energy balance and incorporates spatially distributed snow coverage and snow sublimation. This snow model handles the snow interception and canopy processes at the macro-scale and considers two layer formulation- surface layer and pack layer. Energy exchange takes place from the thin surface layer while the pack layer acts as a reservoir that stores excess snow in the surface layer. The snow model considers all important heat and energy fluxes such as sensible and latent heat, convective energy, and internal energy of the snowpack.

2.3. Data description

The SNOTEL station data are obtained from the National Water and Climate Center of NRCS. The historical data available at each station are daily-accumulated precipitation, snow depth, snow water equivalent, and temperature (max, min, average). These data are available from early 1980's for earlier established stations, and from early 1990's for other stations. The monthly and annual streamflow data, for a period of 1940–2009, are obtained from the United States Geological Survey (USGS). The retrospective meteorological forcing data (precipitation in mm, max and min temperature in degree Celsius, wind speed in m/s), vegetation, soil, and snow band data are obtained from Soil and Water Modeling Group, University of Washington (Maurer et al., 2002; www.hydro.washington.edu/SurfaceWaterGroup/data.php). All of these data are available for 1/8-degree size grid cell for the conterminous United States. The gridded data was prepared through statistical methods and spatial and temporal interpolation of observed data sources. The meteorological forcing data are in a binary format and available at daily time steps for a period of 1949–2000. These data were derived from the hydrologic simulation (at a 3 hourly time step) of land surface energy and water variables over the continental United States. The daily wind speed (m/s) represents wind speed measured at an average height of two meters above the surface.

There are several parameter files that provide the geophysical information to the VIC model. The soil parameter file contains geographical information for each grid cell, and grid cell soil parameters including initial soil moisture conditions. The vegetation parameter file defines different landcover types that are used during simulation, number of vegetation types and their coverage in each grid cell, and other vegetation parameters (e.g. LAI-leaf area index, root depth). The snow band file contains information on each elevation band that is used by the snow model. The land cover data obtained from the Department of Geography, University of Maryland (http://www.geog.umd.edu/landcover) also contains different landcover types at one kilometer spatial resolution.

2.4. Model simulations

All simulations are performed using the VIC model (version 4.1.1) and its energy balance mode of operation. The VIC model is first calibrated and validated by forcing the historical meteorological data to reproduce the historical trend in streamflow. The most common parameters for calibration include soil parameters such as infiltration, soil depth, base flow velocity, and soil moisture (http://www.hydro.washington.edu/Lettenmaier/Models/VIC). Six snow elevation bands are selected to better represent snow processes for each grid cell. The routing model is not used for this analysis since the basin is small (only 97 grid cells) and the analysis is focused on monthly, seasonal or annual changes in streamflow. The VIC model generates streamflow for each grid cell but the flow between the cells is not performed with routing model in this analysis. Therefore the total simulated streamflow for the watershed is the sum of generated streamflow from all grid cells which represents total streamflow at the outlet of the watershed. A univariate calibration method is followed where most sensitive soil parameters are selected and sensitivity analysis is carried out to finalize each parameter. The sensitivity analysis for each parameter is based on model performance indicators. The commonly used indicators such as Pearson Correlation Coefficient (r), Root Mean Square Error ($RMSE$), Bias percentage, and Nash–Sutcliffe Efficiency (E) are calculated to evaluate the model performance in simulating the observed streamflow. They are calculated as follows (Krause et al., 2005; Wang et al., 2009):

$$r = \frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{(n-1)S_o S_p} \quad (1)$$

$$NSCE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \quad (2)$$

$$Bias = \frac{\sum_{i=1}^{n}(P_i - O_i)}{\sum_{i=1}^{n} O_i} * 100\% \quad (3)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \quad (4)$$

where O_i and P_i represent observed and predicted streamflows respectively; S_o and S_p are sample standard deviations for observed and predicted streamflows; and n is the number of observations.

The VIC model is developed for the watershed and the impacts of WM on streamflow are accessed quantitatively based on an anticipated increase in precipitation due to cloud seeding operations. Precipitation is increased only for the months of cloud seeding operations (November 15–April 15). The National Center for Atmospheric Research (NCAR) is currently evaluating WM operations in the State of Wyoming. However, to date, no estimates have been made for the Wyoming pilot project that could give an actual change (increase) of precipitation in the field. The cloud seeding operations in the North Platte River watershed are expected to increase precipitation up to 10% if all the storms during the months of cloud seeding operations are considered and the program is fully operational. However, this may not be a realistic assumption due to various constraints including operating costs. These operations are focused on the central regions of the watershed with a possibility of extension to other regions based on the result from current operations. Since daily precipitation data are utilized, seeding on a particular day is assumed to increase daily precipitation. Therefore, for Scenario 1, precipitation is increased by a maximum of 5%, which represents that approximately half of the total storms are being seeded during the months of cloud seeding. Scenarios 2 are hypothetical and assume WM activities are expanded throughout the North Plate River watershed. All regions are assumed to be seeded fully for later scenarios during the months of cloud seeding operations.

2.4.1. Scenario1: increase precipitation due to Wyoming WM operations

The existing Wyoming ground based generators for cloud seeding operations are mainly located in the central regions of the watershed. Therefore, 12 grid cells (5 on Sierra Madre and 7 on Medicine Bow ranges) are selected from the central region of the watershed where the impact of cloud seeding is assumed to be relatively higher (see Fig. 2), and if precipitation of half of the total storms during the months of cloud seeding is increased, this results in an approximate increase of 5%. Perhaps the most challenging task in the current research efforts is determining the increase in snowpack due to cloud seeding. NCAR has currently (thru the 2010–2011 winter cloud seeding season) evaluated 108 cases with a goal of evaluating between 150 and 200 cases. Each case consists of evaluating snowpack in two areas, one area in which the cloud seeding activities will influence (increase) snowpack and one area which is not influenced by cloud seeding activities and, thus, can be compared to determine estimated increases in snowpack. NCAR's results (estimated increase in snowpack due to cloud seeding) may be available in 2012. NCAR Breed (2008) and Griffith et al. (2007) have estimated increases of snowpack of 10 to 15% due to cloud seeding activities. Thus, the upper limit (5% increase in snowpack due to cloud seeding) used in this research is completely reasonable based on the assumption of a 10% increase in snowpack and that 50% of the storms will be impacted. Additionally, an argument could be made that this upper limit is in fact conservative based on (1) that cloud seeding actually increases snowpack by more than 10%; (2) that the 50% of storm events that are seeded are typically the higher producing precipitation events and thus would produce more snowpack; (3) the spatial impact of the seeding activities will extend beyond the twelve (12) cells identified in the VIC model; (4) in a fully operational program, more than 50% of the storm events will be seeded. For Scenario 1, precipitation is increased from 0.1% to 5% to quantify the variation in streamflow due to cloud seeding of different percentage of storms in the watershed. New sets of forcing data and hypothetical scenarios are developed by changing precipitation in the past meteorological data. These scenarios are forced into the calibrated VIC model to quantify additional streamflow due to increased precipitation. The simulated streamflows are compared with the historical streamflows (1981–2000) for the watershed.

2.4.2. Scenario 2: increase precipitation for different regions

These hypothetical scenarios are developed to quantify the impact of cloud seeding on different regions of the watershed. Precipitation for half of the total storms during the months of cloud seeding is increased by 5%, but only on certain regions of the watershed. The grids within each specific region (e.g. central west, central east, northeast, northwest, southeast, southwest) are selected for this case. Simulations are then carried out for the whole watershed and the simulated streamflows from these WM scenarios are compared with the historical streamflows to determine the change in water supply.

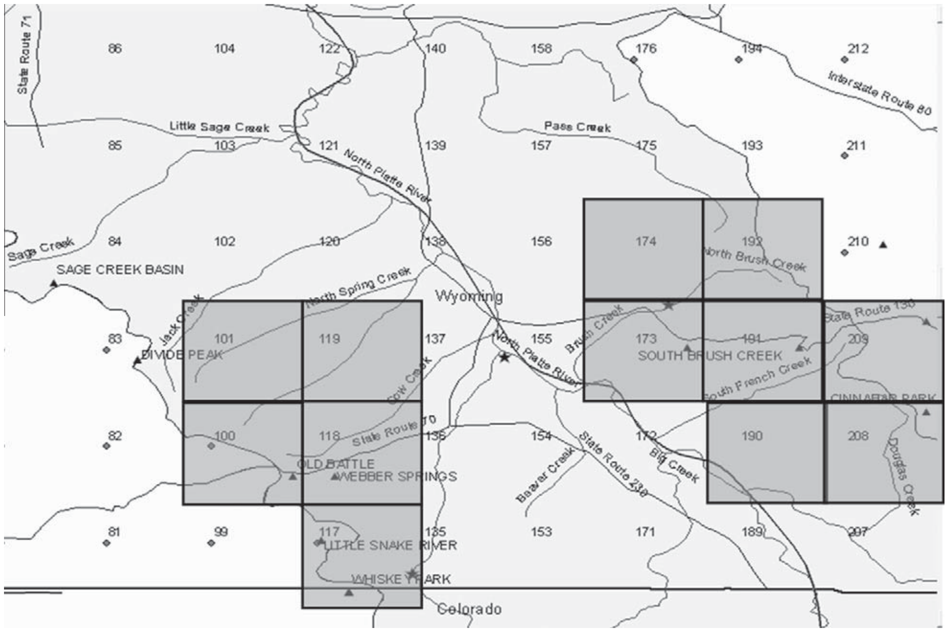

Fig. 2. Central region of the North Platte River watershed where most of the ground based generators are located for cloud seeding operations. The impact of cloud seeding is assumed higher for the highlighted region in this analysis.

3. Results

3.1. Climate observations

3.1.1. Precipitation

The average monthly observed precipitation (mm) is higher during the period of November–April and lower during June–August for the North Platte watershed (Fig. 3). The cloud seeding operations are conducted during the November 15–April 15 period since this is the period of higher precipitation. Maximum monthly precipitation is observed at the Tower station that is located at the southwest border in the Colorado range. The minimum monthly precipitation is observed at the SouthBrush Creek station which is located at the Medicine Bow range.

Fig. 4 shows the spatial distribution of 10 years (1990–1999) average precipitation (mm/year) for the North Platte River watershed. Higher precipitation is observed in the Colorado ranges than the Wyoming ranges of the watershed. The average annual observed precipitation varies from 230 mm to 1385 mm throughout the watershed, with lower precipitation in the northern regions of the watershed.

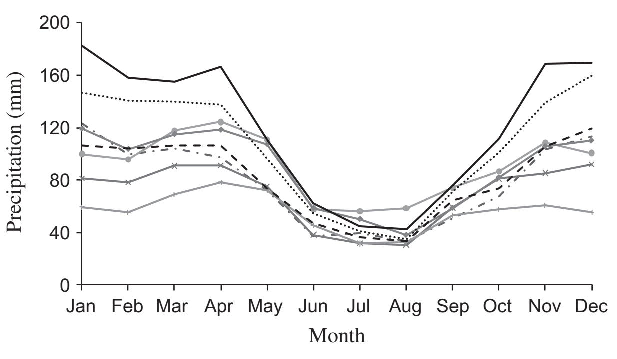

Fig. 3. Average monthly precipitation (1980–2008) for the eight SNOTEL stations in the North Platte River watershed. (C: Columbine; DP: Divide Peak; JW: Joe Write; NFC: North Fork French Creek; OB: Old Battle; SBC: South Brush Creek; T: Tower; WS: Webber Springs).

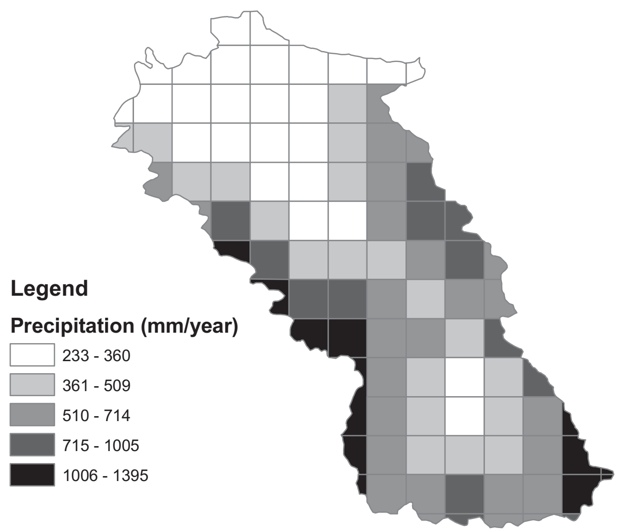

Fig. 4. Spatial distribution of average annual precipitation (mm/year) during the period of 1990–1999 for the North Platte River watershed.

3.1.2. Streamflow

Fig. 5a shows the annual streamflow pattern (1940–2008) for the North Platte River watershed. The USGS gauge‘06630000’ measures total flow from the watershed and is located at the most downstream point of the watershed. The annual observed streamflow from the Wyoming ranges (Fig. 5a – Wyoming only) is higher than the Colorado ranges (represented by USGS gauge ‘06620000’) of the watershed. The streamflow from the Wyoming ranges is determined by subtracting streamflow from ‘06620000’ from ‘06630000’. Both higher and lower annual streamflows are observed at different time periods; maximum annual streamflows are observed during 1980–85. Fig. 5b shows the 10-year (1990–1999) average monthly streamflows for six USGS gauge

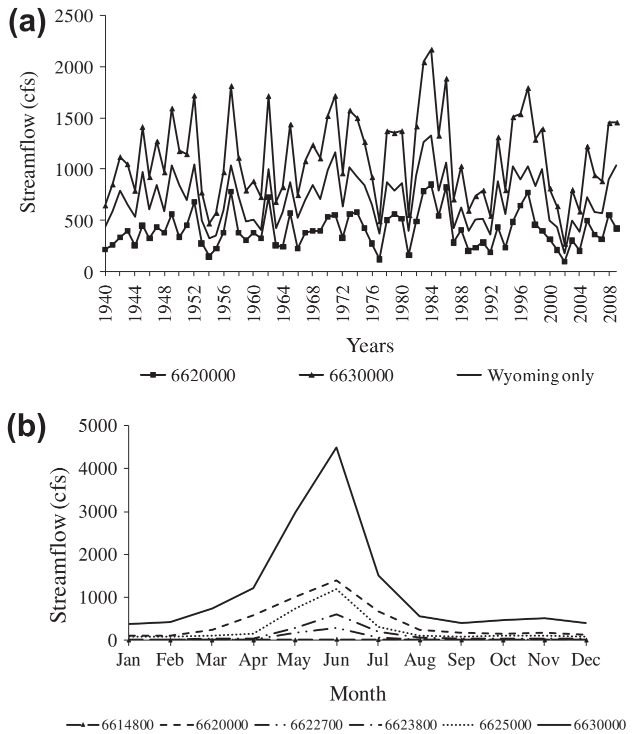

Fig. 5. (a) Annual streamflow (in cubic meters per seconds, cm s) pattern for the North Platte River watershed. '6630000' measure total streamflow for the watershed; '6620000' measures streamflow from the Colorado ranges; 'Wyoming only' represents streamflow from the Wyoming area of the watershed which is obtained by subtracting streamflow from '06620000' from '06630000'. (b) Average monthly streamflow (cm s) during the period of 1990–1999 for six USGS gauge stations inside the watershed.

stations located within the watershed. Higher streamflows are observed during May–July; minimum streamflows are observed during August–February; maximum streamflows are observed during June.

This analysis of historical precipitation and streamflow provides an insight into their temporal variability. It is imperative that such variability be captured through careful model calibration and validation in the ensuing sub-section.

3.2. Model calibration and validation

The model is calibrated and validated with respect to the historical monthly observed streamflow, for the period of 1950–1980 and 1981–2000, respectively (Fig. 6). The monthly data for USGS gauge '06630000', which is located at the most downstream point of the watershed and upstream of the Seminoe Reservoir, is used for this purpose. For the calibration period, a RMSE (5.3 million cubic meters, Mcm), Bias (0.26%), r (0.90) and NSCE (0.79) are obtained, with slight under-estimation of higher peaks and over-estimation of lower peaks. For the validation period, a RMSE (5.8 Mcm), Bias (−2.7%), r (0.87) and NSCE (0.76) are obtained, with under-estimation and over-estimation similar to calibration. A negative bias means the observed streamflows are higher than the simulated streamflows. The infiltration parameter "b_{inf}" and soil depth "$d2$" are found more sensitive in comparison to other parameters during model calibration. The scatter plot in Fig. 6 shows a good correlation between the modeled and observed streamflows at lower magnitudes while increased scatter is found at higher magnitudes. The final calibrated parameters are: infiltration parameter (b_{inf} = 0.19); maximum baseflow (Ds_{max} = 11 mm/day); fraction of Ds_{max} (Ds = 0.04); fraction of maximum soil moisture (Ws = 0.15 mm/day); and soil depth ($d2$ = 0.3 m).

3.3. Weather modification scenario analysis

3.3.1. Change in streamflow: annual and seasonal pattern (Scenario 1)

Simulations are carried out to observe the changes in annual streamflow with respect to an anticipated increase in precipitation for the North Platte River watershed. As discussed earlier, precipitation for half of the total storms of selected grid cells (12) is increased by a maximum of 5%, ranging from 0.1% to 5%; this quantifies additional streamflow from certain regions of the watershed where the impacts of cloud seeding operations are assumed higher for this analysis. Fig. 7a displays the changes in annual streamflow for the Wyoming ranges of the North Platte watershed for an increased precipitation (0.1–5%) during the months of cloud seeding operations. This is streamflow from the total area (grids) located in the State of Wyoming only for the North Platte River watershed; this is comparable to the streamflow obtained by subtracting streamflow from '06620000' from '06630000'. The simulated increase in annual streamflow varies from 0.02% to 2% for a 0.1–5% increase in precipitation. For this range of increased precipitation, the baseline minimum annual streamflow (185.3 Mcm) during 1985 has increased between 185.5 Mcm and 188.8 Mcm, while the baseline maximum annual streamflow (549.3 Mcm) during 1995 increased between 549.5 Mcm and 554.1 Mcm.

The maximum, minimum and average changes in annual streamflow with respect to anticipated change in precipitation are summarized in Table 1. Maximum, minimum, and average values represent the simulated max, min and average changes in annual streamflow for each change in precipitation during the entire period (1981–2000). For an increased precipitation from 1% to 5%, the annual streamflow from the Wyoming area increased from 0.3% to 1.4% (in average); this represents a change in baseline average annual streamflow (354.3 Mcm) between 355.4 Mcm and 359.5 Mcm. This additional streamflow due to cloud seeding operations only in certain regions of the Wyoming corresponds to an average increase of 0.1–0.7% of the total streamflow from the entire North Platte watershed. Future cloud seeding in Colorado may occur using an aircraft in the watershed. As discussed in Section 3.1.1, the Colorado ranges also possess higher precipitation as compared to other regions. Therefore, an increase in total streamflow (than summarized in Table 1) is expected if these regions show a favorable condition for the extension of cloud seeding operations.

The impacts of increased precipitation on seasonal streamflow are also examined for the same period (1981–2000). The observed change (in percent) represents the change in seasonal streamflow for WM scenarios with respect to baseline seasonal streamflow. Fig. 7b shows the change in streamflow pattern during May–June for an increased precipitation due to cloud seeding operations. The seasonal pattern is similar to annual pattern with some years simulating larger changes than other years. During this period, the simulated increase in streamflow varies from 0.1% to 5% for a 1–5% increase in precipitation. The simulated baseline average streamflow (86.5 Mcm) varies between 86.9 Mcm and 88.1 Mcm for this range of increased precipitation. The range of change in streamflow (min, max, average) for the months of May–August (May–June; May–July; June–August) is summarized in Table 2. The period of May–July is considered to contribute almost 70% of annual streamflow for the watershed (Fig. 5a). As indicated in Table 2, average increase in streamflow is also comparatively higher for May–July in compared to other seasons; average increase in streamflow for the Wyoming area varies from 0.5% to 2.5% for a 1–5% increase in precipitation; this corresponds to a change in baseline average streamflow (66.8 Mcm) between 67.2 Mcm and 68.4 Mcm. An

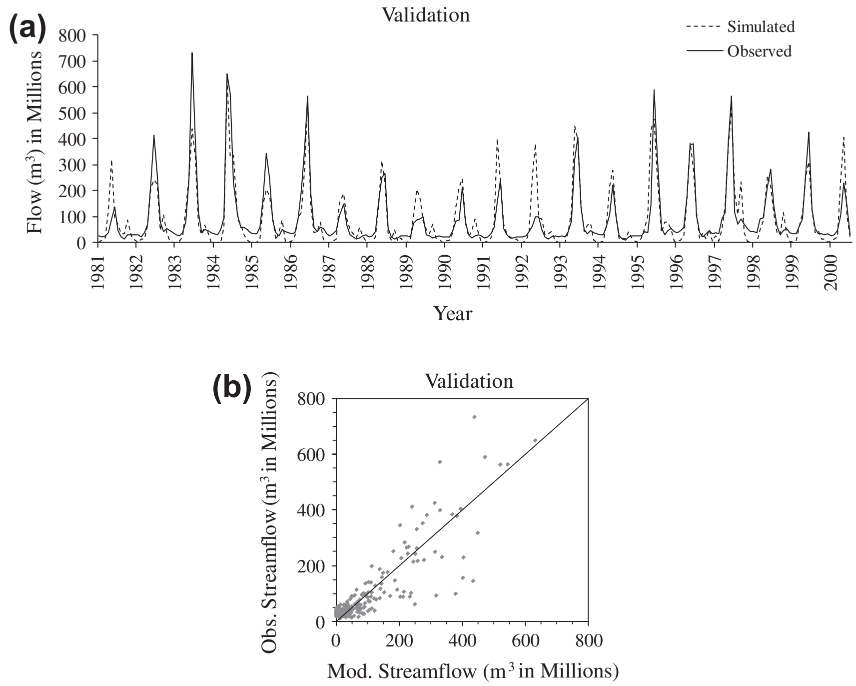

Fig. 6. (a) Variable Infiltration Capacity model validation based on observed monthly streamflow (cubic meters, m^3) during 1981–2000. (b) Scatter plot of observed vs. modeled monthly streamflow during the validation period.

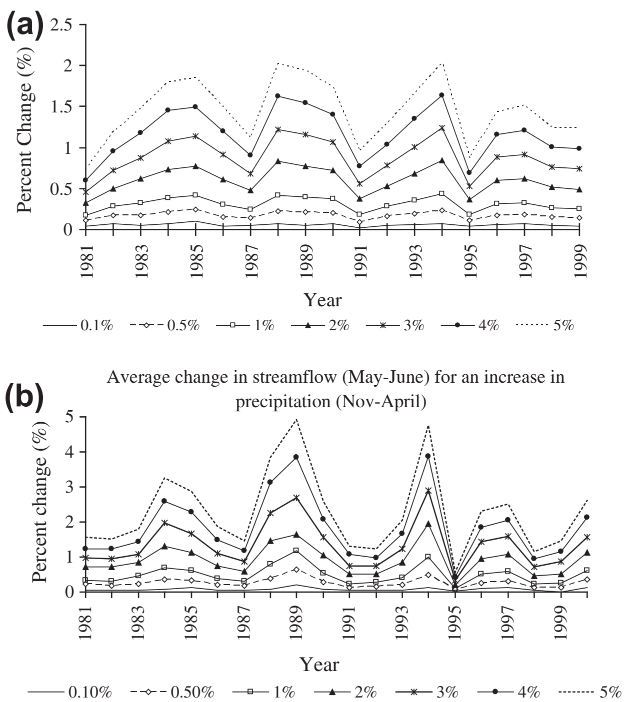

Fig. 7. Percent change in annual and seasonal streamflow with respect to an increase in precipitation (November 15–April 15) from 0.1% to 5% for Wyoming area of the North Platte River watershed. (a) Annual pattern and (b) seasonal pattern.

average increase from 0.4% to 2% is observed during the summer period (June–August) for the same range of increased precipitation.

The higher snowpack accumulation due to wintertime (glaciogenic) cloud seeding operations increases snow cover during the late winter period. The higher snow cover during the winter period gradually melts in a warmer temperature at later periods that contributes to an increased soil moisture and streamflow. A successful implementation of WM programs in this watershed could serve as a viable option to augment precipitation and reduce impacts of declining streamflow during dry periods. However, an additional analysis, which also incorporates the impacts of climate change and water demands, is necessary to fully evaluate the impacts of the WM programs during dry periods.

3.3.2. Region specific change in streamflow (Scenario 2)

This hypothetical analysis determines the impact of WM operations on different regions of the watershed in terms of runoff augmentation. For this purpose, the entire watershed is divided into six regions (Fig. 8): southeast (SE), southwest (SW), central east (CE), central west (CW), northeast (NE) and northwest (NW). Precipitations of the grid cells located within each specific region are increased by 5% and the simulations are carried out for the whole watershed; the simulations are continued for all regions, one region at a time, that considers increased precipitation for the specific region only. However, the set of total storms that are seeded may be different in between the regions since each grid may possess different set of upper half of the storms. Although the central and southern regions occupy comparatively larger areas than the northern regions, precipitation is increased to an equal area (eight grids fully located inside each region) for all regions during this analysis. This area is selected based on the total number of grids fully located in the northern (NE, NW) regions. Same amount of precipitation augmentation on various regions is translated into different streamflow increase. The simulated increases in annual streamflow for the Colorado range of the watershed, which is located on the southern region (SE, SW), vary from 2% to 4% of the annual streamflow for that region (Fig. 9); the median increase is calculated as 2.5% and 3.2% for SE and SW respectively.

The simulated increases in total annual streamflow (measured at USGS gauge '06630000') from the entire watershed vary depending on regions of increased precipitation. An increase in streamflow from 0.2% to 3% is simulated for different regions, where a median increase of 1.50% and 1.62% is simulated for CW

Table 1
Change in annual streamflow for the Wyoming ranges and the whole North Platte River watershed (which includes the Colorado ranges also) for an anticipated increase in precipitation due to cloud seeding operations in the watershed.

Change in precipitation (%)	Change in annual streamflow (%)					
	For Wyoming area			For full North Platte		
	Min	Max	Average	Min	Max	Average
0.1	0.02	0.10	0.06	0.02	0.06	0.04
0.5	0.10	0.24	0.17	0.06	0.16	0.10
1.0	0.17	0.44	0.32	0.11	0.29	0.17
2.0	0.32	0.85	0.61	0.20	0.54	0.32
3.0	0.46	1.24	0.89	0.28	0.78	0.46
4.0	0.60	1.64	1.19	0.36	1.03	0.61
5.0	0.73	2.03	1.48	0.45	1.27	0.75

Table 2
Change in seasonal streamflow for the Wyoming ranges during the cloud seeding operations in the North Platte River watershed.

Change in precipitation (%)	Change in seasonal streamflow (%)								
	May–June (MJ)			May–June–July (MJJ)			June–July–August (JJA)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
0.1	0.01	0.21	0.07	0.01	0.15	0.07	0.03	0.15	0.08
0.5	0.08	0.64	0.26	0.11	0.66	0.27	0.07	0.60	0.26
1.0	0.09	1.16	0.49	0.20	1.33	0.53	0.12	1.19	0.48
2.0	0.21	1.94	0.91	0.34	2.62	1.02	0.18	2.33	0.90
3.0	0.32	2.90	1.36	0.51	3.88	1.51	0.26	3.44	1.35
4.0	0.43	3.87	1.83	0.66	5.18	2.03	0.33	4.58	1.81
5.0	0.56	4.91	2.28	0.83	6.45	2.54	0.41	5.69	2.20

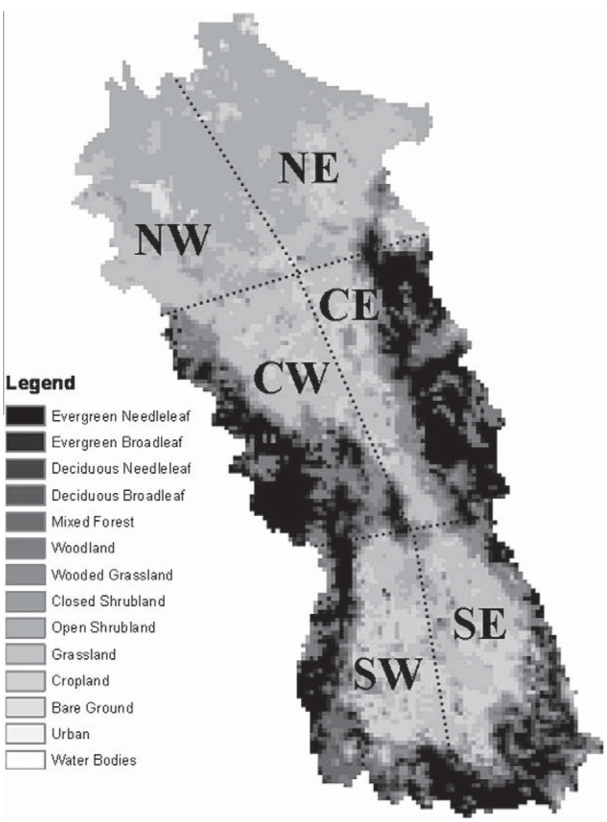

Fig. 8. North Platte River watershed showing different types of land cover and regions for cloud seeding operations considered for this analysis.

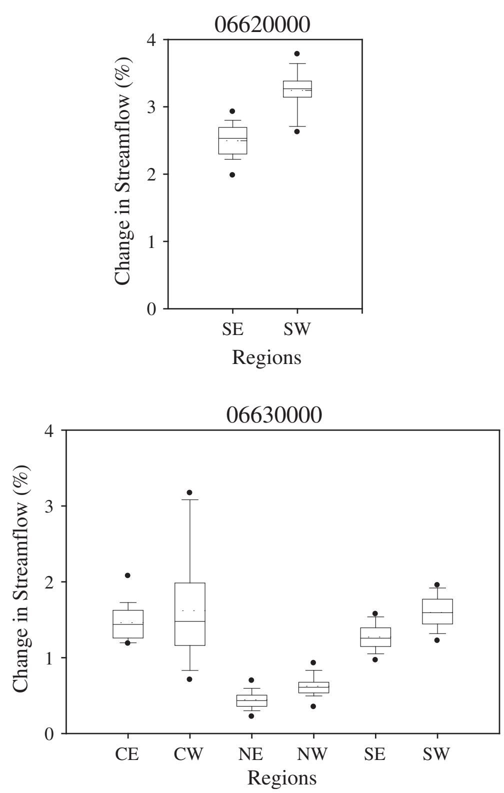

Fig. 9. Boxplots of percentage change of annual streamflow for USGS gauge 06620000 and 0663000, when precipitation is increased by five percent for specific regions (Fig. 8) only. (NE: north-east; NW: north-west; CE: central-east; CW: central-west; SE: south-east; SW: south-west).

and SW regions respectively. The median change in streamflow is higher for SW while the maximum increments are shown by CW. Southern regions have shown higher contribution for increased streamflow for the Colorado ranges as well as the entire watershed. A comparatively higher streamflow from southern and central regions may be due to higher precipitation in these regions than the northern regions of the watershed (Fig. 4). The simulated increase in streamflow from central and southern regions could be expected higher if all the grids are considered from these regions, since the grids with higher precipitation located at the border of the watershed (not fully within the watershed) are not considered in this analysis. Fig. 10 shows the spatial distribution of percentage of total annual precipitation falling on each grid. This percentage is based on average annual precipitation for each grid with respect to average total annual precipitation for the entire watershed during 1990–1999. About 80% of the total annual precipitation for the watershed falls on the central and southern regions. The operational cloud seeding programs are conducted over the Medicine Bow and Sierra Madre ranges of the watershed which are located at central regions. Higher annual precipitation in central and southern regions may be attributing for larger changes in annual streamflow from these regions during cloud seeding operations. The lower annual precipitation in northern regions may be attributing for minimal changes in annual streamflow from these regions during cloud seeding operations.

Fig. 8 shows different types of landcover in the watershed (Evergreen Needleleaf Forest, EG; Open Shrublands, OS; Grasslands, GL; Woodland, WL; Wooded Grasslands, WGL; Deciduous Broadleaf Forest, DF; Mixed Forest, MF; Closed Shrub lands, CS; and Crop lands, CL). The CW regions have higher coverage of WL, EG and GL; SW regions have higher coverage of EG, and lower coverage of a combination of WL, WGL, CL and GL; the northern regions have higher coverage of OS and GL. Fig. 10 shows the spatial distribution of annual precipitation and major landcovers inside the watershed. Major landcover here represents the dominant landcover (maximum coverage) within each grid. During WM operations, changes in simulated streamflows from different regions may be primarily due to variation in precipitation distribution within the watershed (Figs. 4 and 10), and secondarily due to the properties of landcover and soil present in different regions of the watershed. Within central and southern regions, the areas that receive higher precipitation has shown larger EG landcover (Fig. 10). The saturated hydraulic conductivity of soil is similar for all regions. But the initial layer moisture content is approximately three times higher for the central and southern regions as compared to the northern regions; this may contribute to the higher and earlier peak runoff from these regions. The minimal change in streamflow from northern regions may be attributed to higher evaporation and lower initial soil moisture. The thickness of soil moisture layer and average soil temperature that are used as the bottom boundary for soil heat flux solution in the VIC are also higher for the northern region. This may influence the water budget and energy balance and increase evaporation (evapo-transpiration) which further reduces total runoff, and slows down the time for seasonal peak flows from this region.

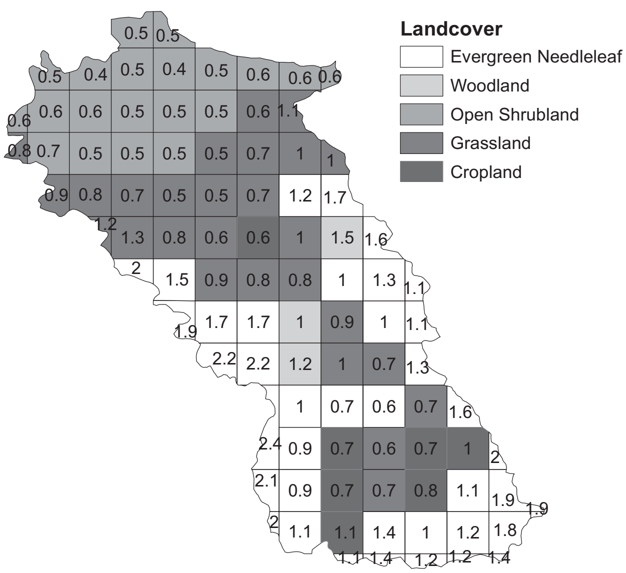

Fig. 10. Dominant landcover for each grid and percentage of total annual precipitation (central value) shared by each grid. Percentages for each grid are calculated based on average annual precipitation for each grid with respect to average total annual precipitation (during 1990–1999) for the entire watershed.

4. Conclusions

This paper developed a hydrologic model (within VIC) to evaluate the impacts of WM programs on water supply. The impacts have been evaluated in terms of change in streamflow. This paper also provided a proof of concept for development and application of WM scenarios for hydrologic impact evaluation. The concept of modeling and WM scenario analysis as presented here can be implemented to any WM projects to observe their impacts on water supply.

The corresponding changes in streamflow are quantified as a result of cloud seeding operations in the North Platte River watershed. With effective WM programs, the increased precipitation could augment annual and seasonal streamflow and reduce the impact of declining streamflow during dry periods. An increase of 0.3–1.5% in annual streamflow is observed for an anticipated increase of precipitation from 1% to 5%. The present cloud seeding operations are conducted on the central regions of the watershed. This research has found the central west and southwest regions of the watershed to generate higher streamflow during cloud seeding operations. The northern regions are found to generate lower changes in streamflow during these operations. However, the simulated changes in streamflow may not be considered as changes due to cloud seeding operations alone. The observed annual precipitation is higher for central and southern regions in compared to northern regions of the watershed. Therefore, changes in annual streamflow from different regions and landcovers could also be attributed to variation in precipitation distribution within the watershed rather than the effect of cloud seeding operations only.

The impacts of WM programs on water supply can be evaluated based on this analysis. The results presented here can also be utilized directly by the WM projects operating at representative watersheds. Further work will estimate the impacts of WM on other hydrologic parameters (e.g. soil moisture, reservoir level, evapotranspiration, and snow water equivalent).

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