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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-