Using SWAT Model and Snow Survey Data to Assess Spatial Variability of Snowpack in the Cannonsville Watershed, New York, USA

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ABSTRACT:

Snowpack is an important component of the water resources of the Cannonsville watershed in New York State, the location of the West-of-Hudson portion of New York City water supply. The distribution of snow is non-uniform across the landscape due to changes in elevation as well as number of other factors. The need for understanding snowpack distribution and snow melt in the Cannonsville watershed is due to the fact that the hydrologic regimes of high elevation headwaters are linked to streamflow and channel processes in low-elevation stream reaches that serve as inputs to water supply reservoirs. Snowmelt hydrology is an important component of the Soil and Water Assessment Tool (SWAT) model in watersheds where spring runoffs are strongly affected by melting snow. Snowmelt runoff algorithms that do not consider the effect of elevation changes may inaccurately predict spring runoff and nutrient load associated with such events. This study compares model simulated snow pack and melts at different elevation bands to the snow survey data available for Cannonsville watershed. These simulations examine if modeled snow data can be reliably used for future water quality simulations using SWAT model. In addition, the effect of climate change was also evaluated. Our results showed that the snow survey data compared fairly well with the snow pack simulated by the SWAT model. Simulations of streamflow improved when using three elevation bands. Streamflow simulations showed lower model performance using snow survey site elevation, due to the snow survey sites being somewhat biased toward lower elevations.

Keywords: elevation, snow water equivalent, snowmelt, streamflow, SWAT

INTRODUCTION

Snow is an important component of the hydrologic cycle particularly in land area poleward of about 40° latitude. (Adam et al., 2009). The properties of fallen snow change continuously as a function of energy fluxes, wind, moisture, water vapor, and atmospheric pressure. Hence in these regions, knowledge of snowfall amounts, the amount of snow accumulation on the ground (snow cover), and their spatial distribution is essential for effective planning, management, and adaptation of water resources to climate change.

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The most important snow data that snow hydrologists use is the snowpack snow water equivalent (SWE) (Dingman, 2002) and snowmelt. The SWE is defined as a mass of water contained in the snow pack and is expressed units identical to precipitation i.e. mm (Paul et al., 2004). The SWE (1) is the measure of snow used in snow runoff analysis to determine the quantity and distribution of snow; (2) is the primary determinant governing the magnitude of the snowmelt runoff volume; and the distribution of the snowpack in the basin; and (3) is the factor determining the rate of melt during the melt season. In a basin during the winter accumulation period, the SWE responds, either directly or indirectly, to a variety of meteorological and topographical interactions that influences snow accumulation and distribution.

Snowmelt is a significant surface water input of importance to many aspects of hydrology including water supply, erosion and flood control (Tarboton et al. 1995). The processes involved in snowmelt have been widely described (Dingman 1994; Tarboton et al. 1995; USACE, 1998; You et al. 2004). Snowmelt is modeled with different approaches from simple regression methods and approaches based only on temperature measurements to physics-based models involving all process (Ferguson 1999) or based on an energy balance (Marks et al. 1999; Walter et al, 1996). Due to simplicity and ease of use, temperature index based empirical models are frequently used to estimate snowmelt compared to complex, data intensive energy budget snowmelt models (Zhang et al. 2008).

In river basins with significant elevation variations, low temperatures, and large areas, and complex topography including a variety of slopes and aspects, the snow accumulation and melt processes are significant and highly spatially variable (Debele et al., 2008; Zhang et al. 2008) and there is a need to model these processes in a continuous and distributed way. Correctly modeling snowmelt in a hydrologic model is especially important because incorrectly simulated snowmelt result in inaccurate predictions of flow for that day (Frankenberger et al. 1999; Fontaine et al. 2002).

The most common approach in the distributed basin formulation is to subdivide the basin into zones and/or bands based upon elevation. Most snowmelt runoff models handle spatial and temporal variations due to elevation by incorporating elevation bands allowing the model to discretize the snowmelt process based on watershed topography (Rango and Martinec, 1995; Hartman et al., 1999). For each elevation band, precipitation, snow, soil moisture, etc., are simulated independently; then moisture output from each band is totaled to obtain input into the hydrologic model routines dealing with soil moisture and stream runoff.

This methodology of distributed snow modeling in elevation bands is employed with reasonable success to account for changes in the snowpack (USACE, 1998) and is employed in this study using SWAT 2005. The study region shows a variation in elevation (300-1100 masl), and shows geographical, hydrological, and meteorological conditions that are typically related to elevation. The accounting of SWE is done by dividing basin into various elevation bands (up to 10 in SWAT 2005 model). This will account for all the physical changes that occur during snowmelt. In this study each band is assumed to be snow covered with equal fraction.

This study examined the accuracy of the SWAT 2005 model simulating snowpack SWE and snowmelt influenced stream flow. The objectives of this study were:

To evaluate the performance of SWAT model's temperature index based snowmelt algorithm in simulating snowpack. We compared the snowpack output from SWAT 2005 model to the snow survey data collected by the New York City Environmental Protection (NYCEP).

To evaluate model performance in predicting daily streamflow using three different distributions of elevation bands: snow survey site elevations, and the SWAT-defaults of 3 and 5 elevation bands.

To assess changes in annual snowfall and snowmelt for Cannonsville Watershed with change in climate using four climate scenarios.

SITE DESCRIPTION

The Cannonsville watershed is one of New York City's largest drinking water reservoirs and is located in Delaware County in the Catskill region of New York (Figure 1). The major land uses in the 1178 km^2 Cannonsville watershed are forests (59% of the land area), pasture (26%) and succession farmland (10%). Mean annual precipitation at the Walton, NY climate station is about 1100 mm/yr, of which approximately one third falls as snow. The elevation of the watershed ranges from approximately 300 m above mean sea level in the lowland areas to approximately 1100 m in the uplands while the average land-surface slope is 19%. The development of snowpack in this region is variable. Snow accumulation can begin as early as November and snowpack can persist until late April. However, a continuous and progressive increase in the snowpack over the winter is not common. Snowpack SWE varies throughout the winter as a consequence of intermittent melt and rain on snow events. By March – April the snowpack typically begins to ripen and melt water is released to stream resulting in the highest discharge of a year.

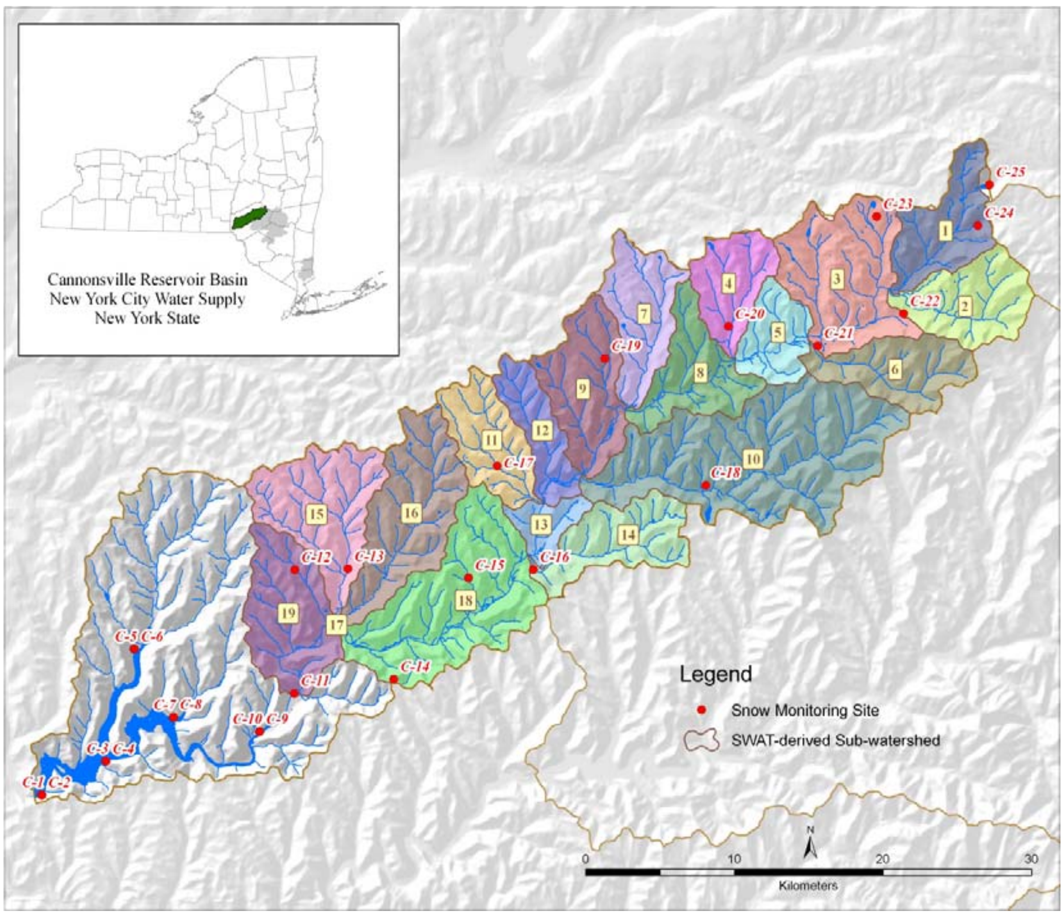

Figure 1. Cannonsville Watershed and snow survey sites.

METHODS AND DATA

The SWAT 2005 model (Neitsch et al., 2005) uses a simple snowmelt algorithm that requires readily available daily measurements of temperature and precipitation as inputs. The model allows the sub-basins to be divided into a maximum of ten elevation bands to account for elevation gradients and therefore spatial differences in snow accumulation and melt. In SWAT, a watershed is divided into a number of sub basins for modeling purposes. Within sub-basins Hydrological Response Units (HRU) are further delineated, based on land use, soil attributes and slope (Neitsch et al., 2005). The proper inclusion and representation of available watershed specific spatial data is crucial in defining representative HRUs. Calibration efforts (i.e. the adjustment of model performance by optimization of parameters) for streamflow focused on improving model predictions, by comparing to measurements at the stream gauging station at Walton (Figure 1).

The SWAT snowmelt algorithm requires daily precipitation, minimum and maximum temperature data. These data were obtained from cooperator stations recognized by the National Climate Data Center and obtained from the Northeast Regional Climate Center. A digital elevation map (DEM), soil data from detailed State Soil Survey Geographic Database (SSURGO) and land use coverage (National Land Use Land Cover 2001) were input to ArcSWAT (Neitsch et al., 2005) in order to create SWAT 2005 model inputs. A total 19 sub-basins were (Figure 1) delineated in ArcSWAT using 10m DEM for Cannonsville watershed. Model simulations were run for 12 years (1989-2000) with the first 2 years used for initialization. Model performance on daily streamflow was qualitatively evaluated with time series plots and quantitatively evaluated using two model performance statistics. The coefficient of determination (r^2) and the Nash-Suttcliffe coefficient (E_{NS}) (Nash & Suttcliffe, 1970) were used to assess the ability of the model to replicate temporal trends (daily and monthly) in measured stream flow data. The SWE from snow survey data at each site were compared to model simulated SWE at each sub basin corresponding to snow survey site for 2004-2008 period using correlation coefficient. The streamflow simulations based on elevation data from snow survey site, SWAT-default elevation, 3-elevation bands and 5-elevation bands were also compared for the SWAT model performance.

Snowmelt Algorithm in SWAT

The snowmelt algorithm in SWAT consists of simple temperature index method that allows sub-basins to be further divided into maximum of ten elevation bands. The major climate data needed for this purpose are maximum and minimum temperature and precipitation. When the mean daily air temperature is less than the snowfall temperature, as specified by the variable SFTMP, the precipitation within an HRU is classified as snow and the liquid water equivalent of the snow precipitation is added to the snowpack. The snowpack increases with additional snowfall, but decreases as snow melts or sublimation occurs. The mass balance for the snowpack is computed as:

$$SNO_i = SNO_{i-1} + R_{sf_i} - E_{sub_i} - SNO_{mlt_i}$$

where SNO_i and SNO_{i-1} are the water equivalents of the snowpack on the current day (i) and previous day ($i-1$), respectively, R_{sfi} is the water equivalent of the snow precipitation on day i, E_{subi} is the water equivalent of the snow sublimation on day i, and SNO_{mlti} is the water equivalent of the snowmelt on day i. All of these variables are reported in terms of the equivalent water depth (mm) over the total HRU area. The snowmelt is calculated as a linear function of the difference between the average snow pack maximum air temperature and the base, or threshold, temperature for snowmelt (Neitsch et al., 2005).

In order to use the elevation band algorithm, for each sub-basin, the average elevation of each band and the percentage of the sub-basin area within that band are required (Fontaine et al., 2002). In this study, 3 and 5 elevation bands (with equal area) were established for each sub-basin. The temperature and precipitation are calculated for each band as a function of the respective lapse rate and the difference between the gage elevation and the average elevation specified for the band using following equations:

$$T_B = T + (Z_B - Z)\frac{dT}{dZ}$$

$$P_B = P + (Z_B - Z)\frac{dP}{dZ}$$

where T_B, is the elevation band mean temperature (^oC), T, is the temperature measured at the weather station (^oC), Z_B is the midpoint elevation of the band (m), Z is the weather station's elevation (m), P_B is the mean precipitation of the band (mm), P is the precipitation measured at the weather station (mm), dT/dZ is the precipitation lapse rate (mm/km), and dP/dZ is the temperature lapse rate (^oC/km). The temperature lapse rate of 6^oC/km was used in this model.

Model Modification

The authors tried to limit modifications to the distributed SWAT code base, and ArcSWAT initialization system in order to obtain SWAT output for each elevation band for each sub-basin. Modifications were made only in term of snow melt and snow pack output at each sub-basins at each elevation band. Open, write and format statements were added to snom.f and clicon.f subroutines. Several variables had to be tracked through the model run, so modifications had to be made to the writem.f and writed.f subroutines to account for daily and monthly outputs.

Snow survey and meteorological data

Snow pack water equivalent (SWE) and depth data measured were obtained from New York City Environmental Protection (NYCEP) for 2004 through 2008 for Cannonsville watershed. The NYCEP conducts snow survey every two weeks from January 15 through mid April (Figure 1). An initial volume of SWE is determined at the beginning of the snowmelt period. As the melt season progresses, calculated melt is subtracted from the initial values to yield a residual, and any additional precipitation is added.

CLIMATE SCENARIOS

The potential effect of climate change on snowfall and snowmelt was evaluated using 4 climate scenarios, i.e., GFDL A2, GFDL B1, IPSL A2 and IPSL B1 (Table 1), which represent a wide range of future climate conditions. The climate scenarios developed in this study were downscaled using delta change factor methodology of Anandhi et al., (2010).

Table 1 Climate scenarios used in this study

Climate Models	Scenarios	Description	Change Factor[a]	
			Precipitation	Temperature
GFDL 2.0	A2	Atmospheric CO_2 concentration reach 850 ppm in the year 2100 in a world characterized by high population growth, medium GDP growth, high energy use, medium/high land-use changes, low resource availability and slow introduction of new and efficient technologies.	1.05	5.35
IPSL	A2		1.04	6.55
GFDL 2.0	B1	Atmospheric CO_2 concentration reach 550 ppm in the year 2100 in a world characterized by low population growth, high GDP growth, low energy use, high land-use changes, low resource availability and rapid introduction of new and efficient technologies.	1.08	2.65
IPSL	B1		1.05	3.98

[a.] Change factors for each month were calculated and averaged over 12 months period

RESULTS

Snow water equivalent comparison

Snowpack comparison between SWAT 2005 snowmelt algorithm and NYCEP snow survey data showed highly variable results. The inaccuracy of model predicted snowpack SWE depended upon the spatial and temporal scales of comparison. Results were therefore compared at a number of different scales, that were representative of both spatial, temporal variability. The comparisons were also segregated by year. A correlation coefficient of 0.61 was obtained for the median (2004) snowpack SWE when simulated SWE was compared to measured data at each individual snow survey point (Figure 2). Since the number of sites decreased in succeeding years, the sites available for comparison was less compared to 2004. The median correlation coefficient of SWE was 0.14 for 2008. Snow water equivalent readings for specific dates were correlated with computed SWE for given snow site in the basin. The SWE for several sub-basins were compared against corresponding snow survey site individually for each year from 2004 through 2008, each sites including all years of study and all sites along with all years. Comparisons made for each site for each year however showed mixed results. There were some sites that showed model under-predicting SWE for winter and early spring months whereas sub-basins with relatively higher elevation had SWE under-predicted by the model. Additionally, since many snow survey sites disappeared in year 2007 and 2008, the comparison of snow survey data were limited to very few sites (in 2008, there were only 2 snow survey sites that could be compared). The SWAT default elevation band method showed higher difference in predicted snow melt as compared to 3 and 5 band simulations (Figure 3). The SWAT model may be unable to emulate the intermittent winter snow melting processes, when snow melting maybe triggered by a short-period warm temperature at noon, but the melted snow then refreezes in the afternoon before it can contribute to the stream flows (Debele et al., 2009).

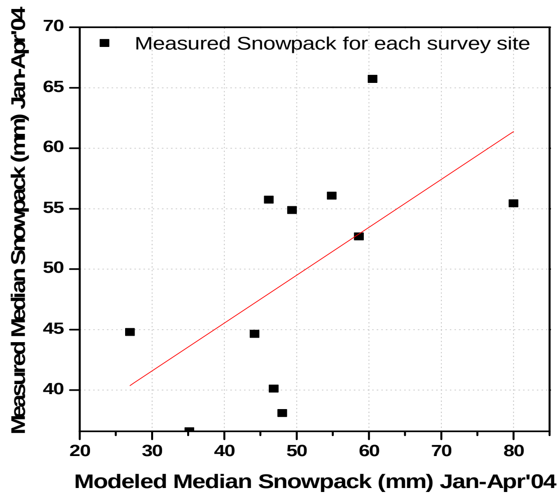

Figure 2. Median Snowpack SWE. comparison for snow survey sites and corresponding sub-basins.

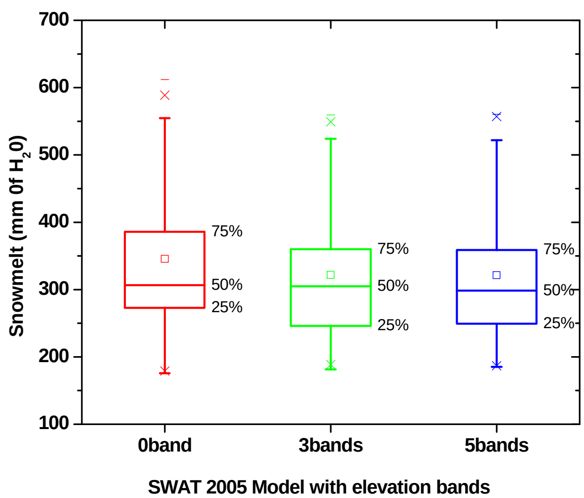

Figure 3. Box-plot showing snowmelt simulated using SWAT default, 3 and 5 elevation bands.

Daily Streamflow comparison

Regardless of the simulation techniques used during the snowmelt, an essential modeling practice for streamflow simulation is to make use to field observations to verify model output, and by doing so gain some insight into the accuracy of the model's state variables. The model's computation of snowmelt was therefore, also checked by comparing computed discharge against streamflow observations. The SWAT 2005 model was calibrated for streamflow from 1991-2000 and was verified for 2004-2008 years. Sensitivity analysis was conducted prior to calibrating the model. Simulated values of daily streamflow were found to be sensitive to five parameters, and these were then used to calibrate the model. The parameters are effective hydraulic conductivity (Ch-K2), Manning's n value for main channel (Ch_N2), initial Soil Conservation Service (SCS) curve number II (CN2), baseflow alpha factor (Alpha-bf), and snow pack temperature lag factor (Timp).

A primary goal of our work with the SWAT model is to effectively simulate stream flow. Here we consider the impacts of different snow parameterization on estimates of stream discharge. For one scenario, the basin wide variables that were related to snowmelt were kept constant in basin file of the model input. The model performance during calibration period showed R^2 of 0.62 and NSE of 0.60 for daily streamflow when using SWAT default elevation for each subbasin, i.e. average elevation of the subbasin. The verification period showed R^2 of 0.58 and NSE of 0.54. The R^2 and NSE values were somewhat higher for the 3-elevation band SWAT simulation, but did not show additional improvements with the 5-band simulation (Table 2). The SWAT default elevation takes into account average elevation for each sub-basin, therefore elevation variability is not completely represented. However given the relatively large number of sub-basins (Fig. 1) relatively large elevation range is covered at the scale of the entire watershed. The further division of each sub-basin into 3-elevation bands apparently provided more accurate estimates of snow accumulation and melt as suggested by better streamflow prediction. Since, the elevation difference within this watershed is not extremely large, using more than 3-elevation band did not produce better results in SWAT simulation. Although the simulation results although showed higher model performance using elevation bands, the computation time for the SWAT simulations increased greatly making runs slower and time consuming. The streamflow simulations for the SWAT model using elevation bands corresponding to the snow survey sites showed lower model performance. This is probably a result of the snow survey sites being biased towards sites at lower elevations.

Table 2 Model performance of daily streamflow using different elevation bands

Statistics	Snow survey elevation	SWAT default elevation	3-elevation bands	5-elevation bands
Nash and Sutcliffe's Efficiency	0.57	0.60	0.63	0.63
Coefficient of Determination (r^2)	0.60	0.62	0.65	0.65

Due to the lack of snow survey sites that represent high elevation areas, the streamflow generating from upland areas during snow seasons are not well represented in the model when elevation bands are based on snow survey elevation. The built-in snow model, although a very simple temperature index based snow model, can therefore be used for streamflow simulation purposes in forest dominated Cannonsville Watershed.

Snow pack distribution

The distribution of snow pack for each sub-basin varied for each month. The snow distribution map for sub basin 10 is presented in Figure 4 as an example. This figure shows spatial distribution of snowfall at 3 and 5 elevation bands for sub-basin 10 which is the sub-basin with the largest difference in elevation.

In general, once a snowpack warms so that it approaches 0^oC, it begins to yield melt water to the soil surface as heat energy is applied at its surface and from the ground below. A decrease in surface albedo allows greater amounts of shortwave radiation to be absorbed as heat energy, further accelerating the melt. As snow melts, first at lower elevations, the snowline begins to climb to higher elevations. This shifts the melting level in the basin to higher and higher elevations as the season progresses (USACE, 1998, Debele et al., 2009). Any precipitation falling during the melt season will encounter a variety of potential situations: it can fall as fresh snow at higher elevations, as rain-on-snow at lower elevations, and as rain on bare ground (with reduced soil moisture) at low elevations.

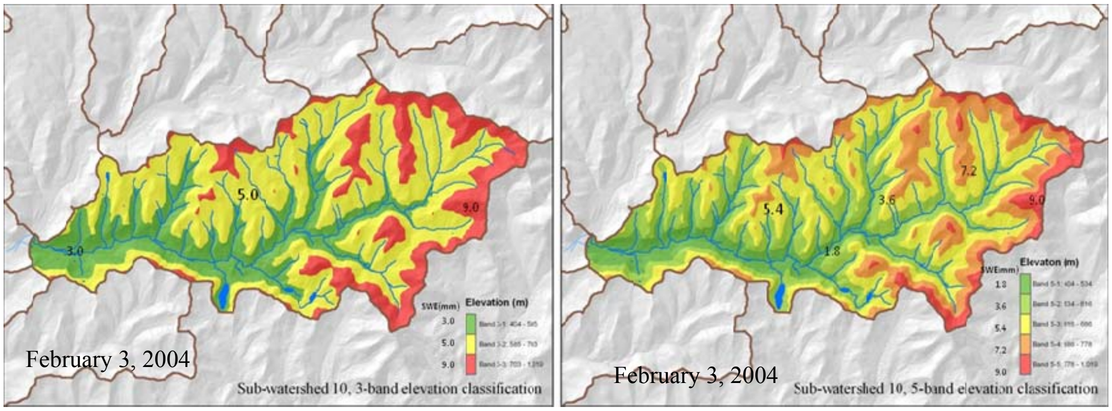

Figure 4. Snow water equivalent distribution for 3 and 5-elevation bands for subbasin 10

The spatial distribution of snowmelt (Figure 5) showed little difference between 3 and 5 elevation bands, but showed higher variability when compared to SWAT default mean sub-basin elevation. The SWAT default elevation takes into account only the average for each sub-basin, therefore not representing elevation dependent snow processes completely. The spatial distribution of the snowpack can be better predicted using three elevation bands, and in addition, streamflow prediction was also improved when using three elevation bands. In relations to water quality it should also be stressed that the processes impacting water quality are simulated at the scale of the multiple HRUs present in each sub-basin. Spatial variations in snow melt can therefore influence relative contribution of each HRU to the water quality component of the SWAT model simulations, and as a result spatial variations in snow melt can have a greater influence on water quality than water quantity.

The total snow water equivalent and snow melt were also compared among each of the sub-basins qualitatively (Table 3). The SWE and snowmelt were higher by 21m and 25 mm respectively for SWAT-default simulation. No difference in annual SWE and snowmelt was observed between the 3-bands and 5-bands simulations. The heights of the snowpack normally increase with the elevation, while the snow melt increase in low elevation. The snowpack within the study watershed mainly accumulated as a result of the snowfall throughout the winter and in early spring; over this period, only a small amount of the snowpack was lost to sublimation (Table 3).

The SWAT simulation using various climate scenarios showed that snowmelt and SWE is expected to decrease at alarming rates. The projected differences are not however, influenced by the use of 3 elevation band or 5 elevation band simulations (Table 3). For these future scenarios temperature was increased significantly and precipitation increased (Table 1).

With increasing temperature and less amount of water available as precipitation, the amount of precipitation falling as snow and snow melt will be greatly affected. Snowpack is very likely to decrease as the climate warms, despite increasing precipitation, for two reasons. It is very likely that more precipitation will fall as rain, and that snowpack will develop later and melt earlier. As a result, peak streamflow will very likely come earlier in the spring, and summer flows will be reduced. Potential impacts of these changes include an increased possibility of flooding in winter and early spring, a reduced possibility of flooding later in the spring, and lower summer flows.

Table 3 SWAT simulated snowfall and snowmelt (mm) annual averages for 2004-2008 periods and 2 climate scenarios using 2 GCMs

Model Runs	Climate Data	SWAT-Default			3Bands			5Bands		
		SWE	$Snow_{mlt}$	E_{sub}	SWE	$Snow_{mlt}$	E_{sub}	SWE	$Snow_{mlt}$	E_{sub}
SWAT Simulations 2004-2008	Present Conditions	362.36	345.08	4.88	341.83	311.43	13.25	341.89	311.30	13.46
SWAT Simulations Climate Scenarios 1926-2008 (Period)	GFDL_A2	175.27	171.89	3.38	171.21	160.67	10.44	170.31	159.32	10.91
	GFDL_B1	111.99	110.69	1.30	107.14	100.69	6.43	106.82	99.98	6.82
	IPSL_A2	132.04	130.15	1.89	127.84	119.98	7.84	127.47	119.18	8.27
	IPSL_B1	67.25	66.8	0.45	65.91	62.09	3.82	65.29	61.14	4.15

Note:
SWE: Snow Water Equivalent in mm
$Snow_{mlt}$: Snowmelt in mm
E_{sub}: Sublimation in mm

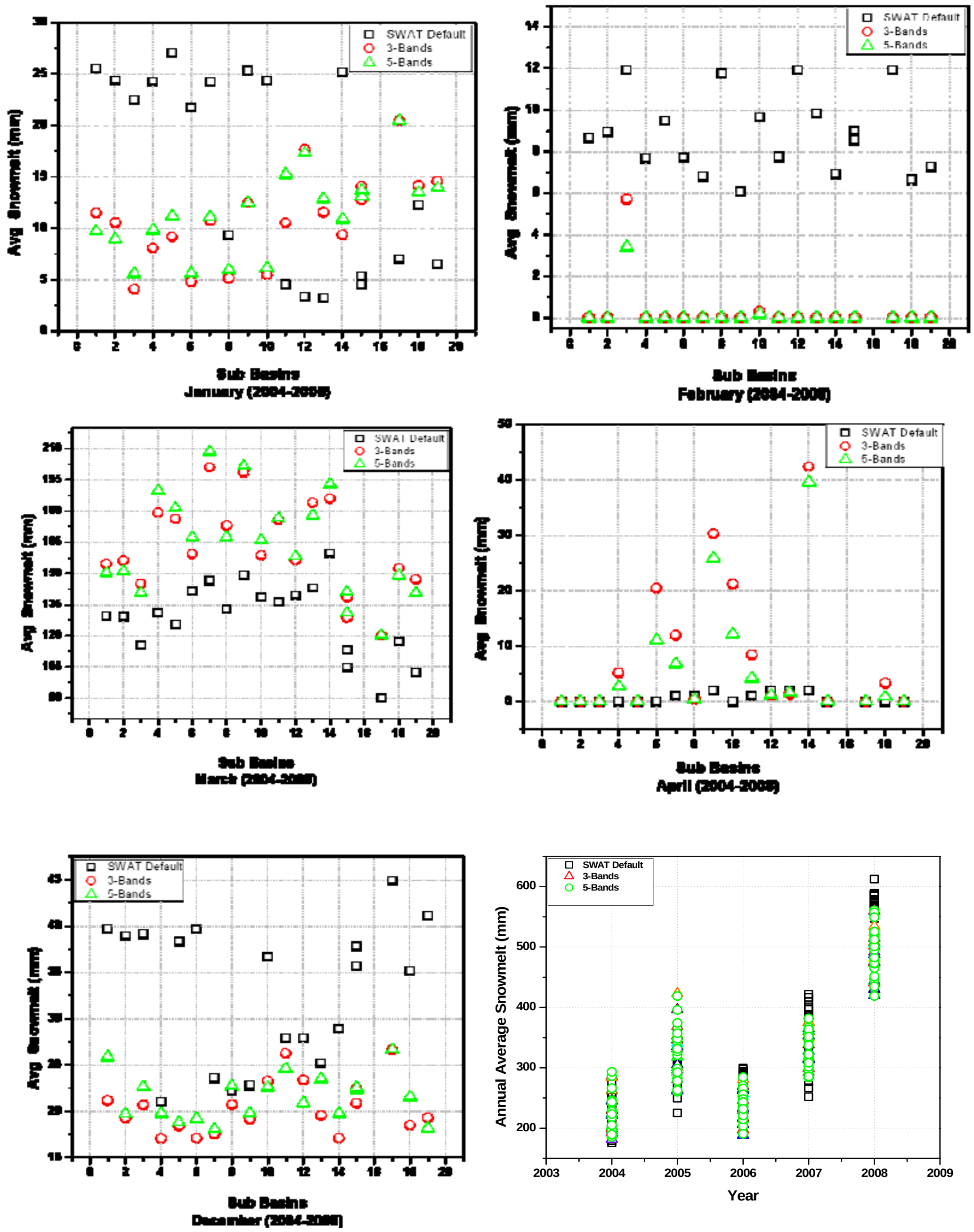

Figure 5. Spatial distribution of snowmelt at monthly and annual scale.

CONCLUSIONS

Accurate representation of variations in the SWAT sub-basin elevation plays important role in snowpack and streamflow simulations. Our results showed that the snow survey data for 2004 through 2008 compared fairly well with the snow pack that was simulated by the SWAT model. Simulations of streamflow were improved when using three elevation bands in each watershed sub-basin. The NSE of 0.63 and r^2 of 0.65 for daily streamflow were obtained for 3 elevation bands simulations. However, using more than three equally distributed elevation bands in each sub-basin led to little improvement in streamflow simulations. Streamflow simulations showed lower model performance using SWAT elevation bands based on snow survey elevation, due to the snow survey sites being somewhat biased toward lower elevations.

In general SWAT model simulates streamflow well for Cannonsville watershed with SWAT-default elevation, 3 and 5 elevation bands. Based on our results SWAT simulation using 3 elevation bands seems to be promising for streamflow modeling. It can however, be computationally time consuming when the number of bands are increased and SWAT outputs for SWE are obtained at each elevation bands. Analyzing data for statistical as well as conceptual modeling in snow hydrology requires additional considerations owing to the nature of the environment and data involved. There are multitudes of uncertainties associated with modeled as well as monitored snow data. Some factors involved are as follows:

- Snow data sampling is sometimes not consistent over a period of record. Sampling techniques have changed (e.g., manual to snow pillow) and station sites are sometimes moved.
- Snow data often have relatively short periods of record compared with precipitation data.
- Precipitation monitoring is more difficult in higher elevation areas. Estimating SWE from precipitation stations may be feasible for high-elevation areas, but it is questionable for areas subject to rain during the winter.
- Orographic effects and sparse gauge density make it difficult to estimate missing data or area-mean quantities.
- Under higher air temperature in future climate change scenarios, SWAT indicate more precipitation falling as rain and reduced snowpack leading to a change in streamflow pattern particularly during winter and early spring.

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REFERENCES

Adam JC, Hamlet AF, Lettenmaier DP. 2009. Implications of global climate change for snowmelt hydrology in the twenty-first century. *Hydrological Processes* **23:** 962-972.

Anandhi A, Frei A, Pierson DC, Schneiderman EM, Zion MS, Lounsbury D, Matonse AM. 2010. Examination of change factor methodologies for climate change impact assessment. *Water Resource Research (in review).*

Debele B, Srinivasan R, Gosain AK. 2009. Comparison of process based and temperature-index snowmelt modeling in SWAT. *Water Resource Management* **24**(6): 1573-1650.

Dingman SL.1994. *Physical Hydrology*. Macmillan: New York; 575 pp.

Fontaine T, Cruickshank T, Arnold J, Hotchkiss R. Development of a snowfall–snowmelt routine for mountainous terrain for the soil water assessment tool (SWAT). *Journal of Hydrology* **262**(1-4):209-23.

Goodison BE. 1978. Accuracy of Snow Samplers for Measuring Shallow Snow Packs: An Update. Proc. of 35th Annual Eastern Snow Conference, Hanover, NH.

Hartman MD, Baron JS, Lamners RB, Cline DW, Band LE, Liston GE, Tague C. 1999. Simulations of snow distribution and hydrology in a mountain basin. *Water Resource Research* **35**(5): 1587-1603

Nash JE, Suttcliffe JV. 1970. River flow forecasting through conceptual models, part i. A discussion of principles. *Journal of Hydrology* **10:** 282-290.

Neitsch SL,Arnold JG. Kiniry JR, Srinivasan R, Williams J R. 2005. Soil and water assessment tool : Theoretical documentation. Version 2005.

Rango A,Matrinec J. 1995. Revisiting the degree-day method for snowmelt computations. Water Resource Bulletin. **31**(4): 657-669.

Tarboton DG, Chowdhury TG, Jackson TH. 1995. A Spatially Distributed Energy Balance Snowmelt Model. In K. A. Tonnessen, M. W. Williams and M. Tranter (Ed.), Proceedings of a Boulder Symposium, July 3-14, IAHS Publ. no. 228, pp.141-155.

U.S. Army Corps of Engineers. 1991. Engineering and Design: Runoff from snowmelt. Engineer Manual 1110-2-1406. Department of Army. Washington DC.

You J, Tarboton DG, Luce C H. 2004. Modeling the snow surface temperature in an energy balance snowmelt model. Lincoln, Nebraska, 68583

Walter MT, Brooks ES, McCool DK, King LG, Molnau M. Boll J. 2005. Process-based snowmelt modeling: does it require more input data than temperature-index modeling? *Journal of Hydrology* **300** (1-4) :65-75.

Work R A, Stockwell HJ, Freeman TG, Beaumont RT. 1965. Accuracy of field snow surveys, Tech. Rep. 163, U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, N. H.

Wang X, Melesse AM. 2005. Evaluation of the SWAT model's snowmelt hydrology in northwestern Minnesota Watershed. *Transactions of the ASAE* **48**(4): 1-18.

Zhang X, Srinivasan R, Debele B, Hao F. Runoff simulation of the headwaters of the Yellow River using the SWAT model with three snowmelt algorithms. *Journal of the American Water Resources Association* 2008 **44**(1):48-61.