Hydrologic modelling of the effect of snowmelt and temperature on a mountainous watershed

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Snowmelt-runoff modelling in a mountainous basin is perceived as difficult due to the complexity of simulation. Theoretically, the snowmelt process should be influenced by temperature changes. It is still controversial as how to incorporate the temperature changes into the snowmelt-runoff model in a mountainous basin. This paper presents the results of a study in the North Fork American River basin where the snowmelt-runoff mechanism is modelled by relating the temperature changes to the elevation band in the basin. In this study, a distributed hydrologic model is used to explore the orographic effects on the snowmelt-runoff using the snowfall-snowmelt routine in Soil and Water Assessment Tool (SWAT). Three parameters, namely maximum snowmelt factor, minimum snowmelt factor, and snowpack temperature lag were analysed during the simulation. The model was validated using streamflow data from October 1, 1991 to September 30, 1994, with and without considering the elevation band. The result of this study suggests that the snowmelt-runoff model associated with the elevation band better represents the snowmelt-runoff mechanism in terms of Nash–Sutcliffe coefficient ($E_{\rm NS}$), R^2, and Root Mean Square Error (RMSE).

1. Introduction

In general, modelling the snowmelt effect in a mountainous basin is challenging due to the difficulties in specifying model parameters and the absence of a specific theory that explains the snowmelt-runoff mechanism. In addition, mountainous areas typically lack sufficient data, which leads to computational demand during simulation (Hartman *et al.* 1999; Fontaine *et al.* 2002). There have been numerous attempts in modelling the snowmelt-runoff mechanism. Arnold *et al.* (1998) found that the snowmelt process appears to be very slow, so they treated it as rainfall precipitation taking zero energy in Soil and Water Assessment Tool (SWAT) simulation. Wang and Melesse (2005) studied the performance of a SWAT model on the snowmelt-runoff simulation in a watershed in northwestern Minnesota, and they concluded that the SWAT model shows acceptable accuracy in simulating monthly, seasonal and mean discharges. Martinec *et al.* (2008) and Tahir *et al.* (2011) used the Snowmelt-Runoff Model (SRM) to analyse the snowmelt-runoff in a Himalayan basin, a high altitude mountainous area. They (Martinec *et al.* 2008; Tahir *et al.* 2011) found that, in the high altitude basin, temperature change is one of the most sensitive input parameters in estimating snowmelt-runoff. Most recently, Kult *et al.* (2012) analysed the snowmelt-runoff by taking into account the process of snowpack melting with respect to the elevation changes in a mountainous basin.

Keywords. Hydrologic model; snowmelt-runoff; orographic effects; elevation bands; SWAT.

According to Fontaine *et al.* (2002), orographic effects make a critical impact on the annual streamflow in a mountainous river basin. Accurate simulation of the orographic effects is therefore crucial to better analyse mountain hydrology. As noted in several studies (Marks *et al.* 1992; Fontaine *et al.* 2002), the mountainous hydrology is essentially influenced by elevation gradients of the terrain. Hence, this study uses a distributed hydrologic model to better represent the spatial variability in a mountainous river watershed. Since 1960s, lumped hydrologic modelling has been a popular method in hydrologic runoff simulation in which a point scale hydrologic value is applied to the entire watershed of interest. However, associated with grid-based hydrologic values and the emergence and evolution of remote sensing technologies, distributed hydrologic modelling became the most common method in hydrologic simulation in the recent past (Kang and Merwade 2011). A spatially distributed hydrologic model is considered to incorporate the changes in meteorological inputs and basin characteristics.

In addition, the complex mechanism between the snowfall and snowmelt makes the analysis of a mountainous basin even more intricate (Luce *et al.* 1998; Fontaine *et al.* 2002). Typically, during a simulation, the computed discharge is compared to the observed one so as to calibrate a hydrologic model. However, during winter, a large portion of precipitation falls in the form of snow, and there is no immediate discharge after the snowfall. Instead, snowmelt is recorded as discharge at a later time when the seasons become warmer (Fontaine *et al.* 2002). This makes it very complicate to model the snowfall–snowmelt process because of the difficulty in computing the discharge of snowfall. In order to handle this complicated process, Fontaine *et al.* (2002) modified the original snowfall–snowmelt routine in SWAT by incorporating snow accumulation, snowmelt, areal snow coverage, and an option to input precipitation and temperature as a function of elevation bands. This study applies the snowfall–snowmelt routine of SWAT to a mountainous watershed and explores location specific parameters and the orographic effects on streamflow in North Fork American River basin. The elevation bands can be used to analyse the snowmelt process based on topographic features of a watershed. SWAT can include up to 10 elevation bands in each subwatershed. Each phase of the modelling process and detailed parameter configuration procedures during simulation are discussed in this paper and analysed the effect of snowmelt and the temperature band on long-term precipitation and streamflow in a mountainous area taking into account these antecedent research findings.

2. Study area and weather data

The study analyses the North Fork American River watershed, which is the longest branch of the American River in northern California. Located in the western side of the Sierra Nevada, the drainage area of the watershed is 886 km^2 (Jeton *et al.* 1996). This watershed is highly forested, with prevailing forests changing from pine-oak woodlands to shrub rangeland, ponderosa pine, and subalpine forest as elevation increases. Much of the forests are secondary-growth due to extensive timber harvesting that supported the mining industry in the late 1800s. Soils in the watershed are predominantly clay loams and coarse sandy loams. The geology of the watershed includes metasedimentary rocks and granodiorite. Figure 1 shows the five National Climate Data Center (NCDC) weather stations in the North Fork American River basin. The climate stations with only additional precipitation data are symbolized as triangles and the stations with only temperature data are represented by squares. Table 1 shows more detailed information of the weather stations. Daily precipitation and temperature data for these stations are available at the NCDC website provided by National Oceanic and Atmospheric Administration (NOAA).

Two studies (Jeton *et al.* 1996; Dettinger *et al.* 2004) show the spatial and temporal variations of hydrologic processes in the North Fork American River basin. The orographic effects create spatial variations of precipitation in accordance with elevation. For instance, mean annual precipitation in Blue Canyon at 1676 m altitude and Auburn at 393 m are 1651 and 813 mm, respectively (Jeton *et al.* 1996). Dettinger *et al.* (2004) show that about two-thirds of streamflow in the North Fork American River basin is rainfall and snowmelt-runoff in winter, and less than one-third is snowmelt-runoff in spring. This study incorporates these snowmelt parameters into the analysis of hydrologic processes at watershed scale. A built-in weather generator function (WXGEN) in SWAT was used to generate missing solar radiation, relative humidity, and wind speed based on long term average values obtained from NCDC. The North Fork American River basin has one active stream gauging station (ID 11427000: latitude 38.94 and longitude 121.02) as shown in figure 1. Located at North Fork Dam, CA, the stream gauging station covers 886 km^2 of drainage area. Daily streamflow data for this station is available from the National Water Information System (NWIS). Marked in figure 1, New Weather Station denotes a newly built weather station that reports precipitation data only, while Temp-Only Weather Stations track only temperature data.

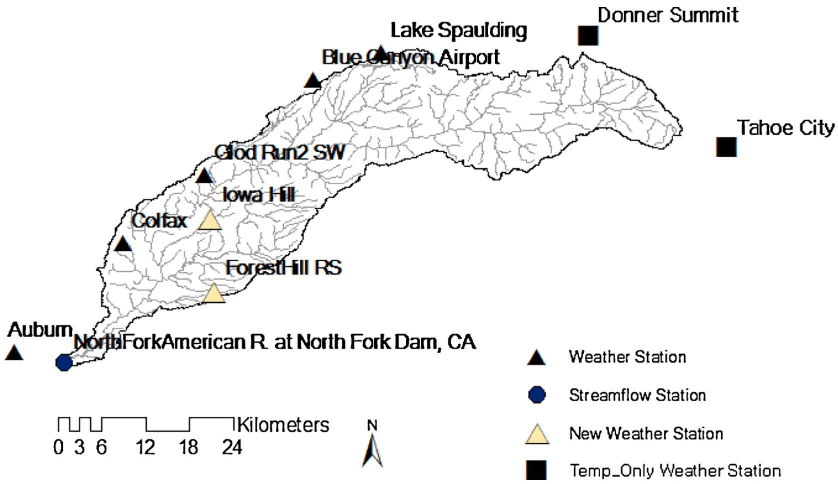


Figure 1. Map of climate and streamflow stations in North Fork American River basin.

Table 1. *Weather stations used for simulation.*

Station ID	Name	Latitude	Longitude	Elevation	MA_P (mm)	MA_T (°C)
40383	Auburn	38.90	121.08	394	914	16.1
43134	Foresthill RS	39.01	120.85	919	1304	N/A
44288	Iowa Hill	39.11	120.83	945	1318	N/A
40897	Blue Canyon AP	39.28	120.71	1608	1500	10.9
42470	Donner Summit	39.31	120.33	2194	N/A	6.4
44713	Lake Spaulding	39.31	120.63	1572	1662	8.8
48758	Tahoe City	39.16	120.15	1899	N/A	7.1
41912	Colfax	39.10	120.95	732	1127	14.6
43491	Gold Run 2 SW	39.16	120.85	1012	1252	N/A

3. Hydrologic modelling

In addition to the weather input, hydrologic modelling requires other input data such as soil type, land use, land cover, and geographic information. These data are available from the United States Geological Survey (USGS). A digital elevation model (DEM) containing layer based geographical information should be pre-processed in a geographic information system (GIS) to create parametric input data for a study watershed. This study uses a 30-m resolution DEM with precise SSURGO soil datasets. SSURGO databases are distributed by National Resources Conservation Service (NRCS) – National Cartography and Geospatial Center (NCGC) and usually available in 1:24,000 resolution. The land cover dataset is obtained from the USGS National Land Cover Database 2001 (NLCD 2001). The land cover dataset has a 30-m grid resolution with a 21-class land cover classification scheme. These geographic input data are used in modelling the study watershed through a series of procedures to process excess precipitation, surface-runoff, infiltration, evapotranspiration, soil and snow evaporation, and groundwater flow.

In SWAT hydrologic modelling, the surface-runoff is estimated by considering excess precipitation with abstractions and infiltration factor through Soil Conservation Service Curve Number (SCS-CN) method. Green-Ampt (GA) infiltration method is another method to calculate the surface-runoff in SWAT. A study (King *et al.* 1999) shows both methods give reasonable results, and there is no significant advantage observed in using one over the other. However, the GA method appears to have more limitations in modelling seasonal variability than the SCS-CN method does (King *et al.* 1999). Hence, the SCS-CN method is used for infiltration factor in this study. An SCS curve number based simulation needs time step updated information as soil water content changes. Excess rainfall equation in SCS-CN method was generated based on historical relationship between the curve number and the hydrologic mechanism for over 20 years. Throughout the surface-runoff calculation, infiltration should be updated over time according to the soil type. Other abstractions such as evapotranspiration and soil and snow evaporation are calculated by Penman–Monteith method and meteorological statistics. Finally, the kinematic storage model is used to compute groundwater storage and seepage. The SWAT has hydrological response units (HRUs) which are divided into multiple subwatersheds (Neitsch *et al.* 2005). HRUs in SWAT are defined as unique combination of homogeneous spatial units with similar geomorphologic and hydrological properties (Neitsch *et al.* 2005). Flow resulting in SWAT modelling is routed HRUs to watershed outlet.

Upon building the model, a spin-up simulation was conducted to ensure appropriate soil moisture and baseflow entered into the model. This study then ran simulation for 4-year periods using streamflow and weather data from October 1, 1987 to September 30, 1994, summarised in table 2. Figure 2 shows the observed streamflow at North Fork Dam used in the simulation. In this study, the accuracy of the model was tested by three statistics: Nash–Sutcliffe coefficient (E_{NS}), R-square (R^2), Root Mean Square Error (RMSE). As shown in equations (1 and 2), E_{NS} and RMSE are used to compare a simulated streamflow to an observed one and represent the accuracy of prediction in hydrological models (Nash and Sutcliffe 1970).

$$E_{\mathrm{NS}} = 1 - \frac{\sum_{i=1}^{n}(Q_{\mathrm{sim},\,i} - Q_{\mathrm{obs},\,i})^2}{\sum_{i=1}^{n}(Q_{\mathrm{sim},\,i} - \overline{Q_{\mathrm{obs},\,i}})^2}, \qquad (1)$$

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n}(Q_{\mathrm{sim},\,i} - Q_{\mathrm{obs},\,i})^2}, \qquad (2)$$

where Q_{sim} is the simulated daily streamflow ($\mathrm{m^3/s}$), $Q_{\underline{\mathrm{obs}}}$ is the observed daily streamflow ($\mathrm{m^3/s}$), and $\bar{Q}$ is the mean daily observed streamflow. Ideally, the E_{NS} should be close to 1 to be considered as an efficient model with acceptable prediction accuracy.

Table 2. *Summary of performed simulations. (Validation(a) is not considering elevation band and validation(b) is considering elevation band in SWAT simulations.)*

Simulation	Period	Observed runoff depth (mm)	Note
Spin-up	1987/10/01–1988/09/30	–	–
First run	1987/10/01–1991/09/30	4134.63	Without snowmelt parameters
Calibration	1988/10/01–1991/09/30	1466.05	With snowmelt parameters
Validation(a)	1991/10/01–1994/09/30	1559.57	Validation without elevation band
Validation(b)	1991/10/01–1994/09/30	1559.57	Validation with elevation band

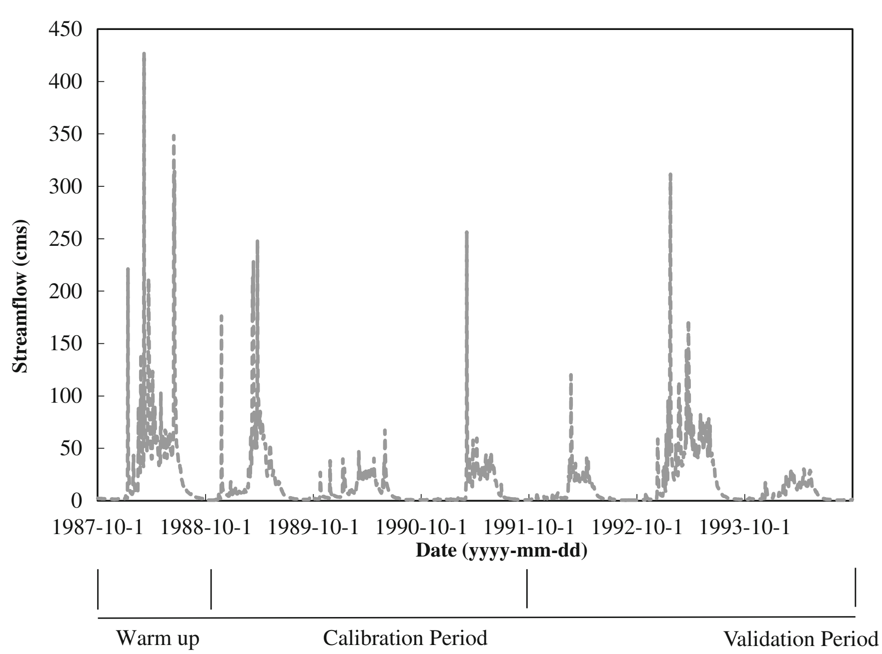


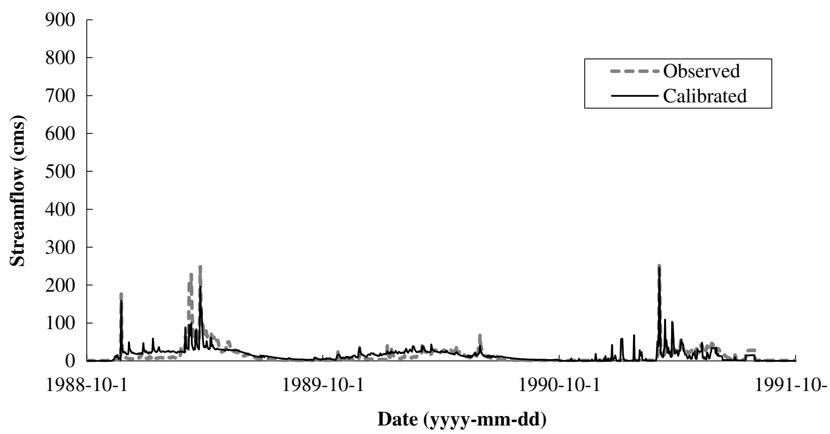
Figure 2. Observed streamflow at North Fork Dam. (**a**) Hydrographs for observed and calibrated simulations. (**b**) Scatter plots with 1:1 line.

4. Model calibration

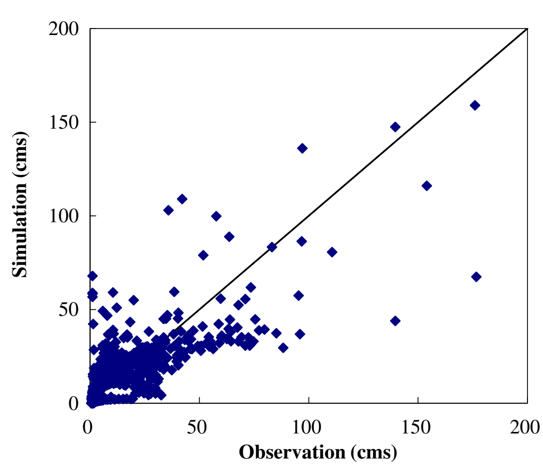
Generally, snowfall does not produce runoff until the temperature rises above the melting temperature whereas the majority of the rainfall can be converted to direct runoff. As a matter of course, the winter runoff may not directly result from immediately preceeding precipitation. According to Hartman *et al.* (1999), one way to incorporate this snowmelt mechanism in a model is by using Snow Water Equivalent (SWE) method, which uses the amount of water contained in the snowpack. The SWE data are convered into the depth of water by dividing the SWE values by the density of the snowpack. In this study, the SWE data were collected from two gauging stations within the study

Table 3. *Summary of the snowmelt-related parameters in SWAT.*

Snowmelt-related parameter	Description	Range	Calibrated value
SFTMP	Snowfall temperature (°C)	–1.5∼1.0	1
SMTMP	Snowmelt base temperature (°C)	0.0∼3.0	0.5
SMFMX	Maximum snowmelt factor (mm H_2O/°C-day)	1.4∼6.9	4.5
SMFMN	Minimum snowmelt factor (mm H_2O/°C-day)	1.4∼6.9	4.5
TIMP	Snowpack temperature lag factor	0.0∼1.0	1
SNOCOVMX	Minimum snow water content that corresponds to 100% snow cover (mm H_2O)	5.0∼35.0	1
SNO50COV	Fraction of SNOCOVMX that corresponds to 50% snow cover	0.5 0.05∼0.35	



(a) Hydrographs for observed and calibrated simulations



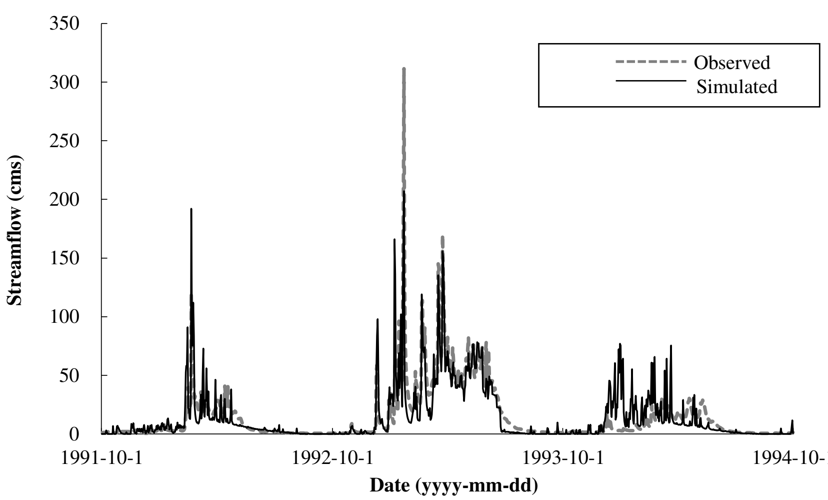
(b) Scatter plots with 1:1 line

Figure 3. Calibrated simulation result. (**a**) Hydrographs for observed and validated (without elevation band) simulations. (**b**) Scatter plots with 1:1 line.

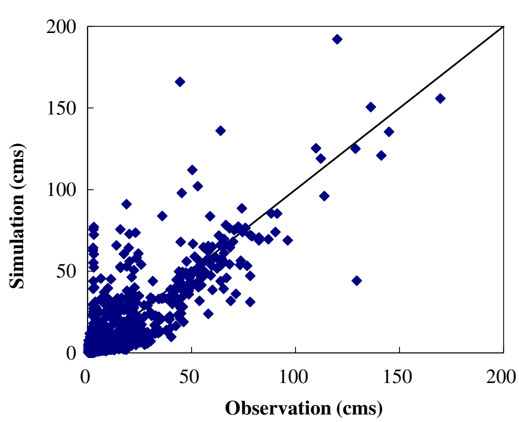
watershed: Blue Canyon and Huysink being operated by the United States Bureau of Reclamation (USBR). These two gauging stations are located at 1609 and 2011 m above sea level, respectively. Daily changes in the SWE data downloaded from the California Data Exchange Center (CDEC) were examined to incorporate the snowmelt effect into simulation. After the data conversion was completed, it was noted that there are too many missing values in the SWE data at Huysink, which makes the precipitation data invalid for simulation. Thus, this study does not use the SWE method to analyse the snowmelt-runoff mechanism. Based on the result of first simulation, it appears that rainfall input is less considerable than snowfall as a modelling input; the model was calibrated in order to better incorporate the snowmelt-runoff mechanism into the model. During the calibration, seven snowmelt-related parameters were calibrated. Table 3 shows the description of each parameter and its value range selected from previous studies (Westerstrom 1984; Huber and Dickinson 1988; Neitsch *et al.* 2002). The snowmelt-related parameters remain constant throughout the simulation in order to analyse the effect of the elevation on the snowmelt-runoff mechanism. Of these seven parameters, the simulation is particularly sensitive to: maximum snowmelt factor (SMFMX), minimum snowmelt factor (SMFMN), and snowpack temperature lag

Table 4. *Elevation band for precipitation and temperature parameters.*

Input parameters	Value
Elevation bands	215–721 m
	721–1228 m
	1228–1734 m
	1734–2241 m
	2241–2747 m
Precipitation lapse rate (dP/dZ)	0.53 mm/m
Temperature lapse rate (dT/dZ)	−5.6°C/km



(a) Hydrographs for observed and validated (without elevation band) simulations



(b) Scatter plots with 1:1 line

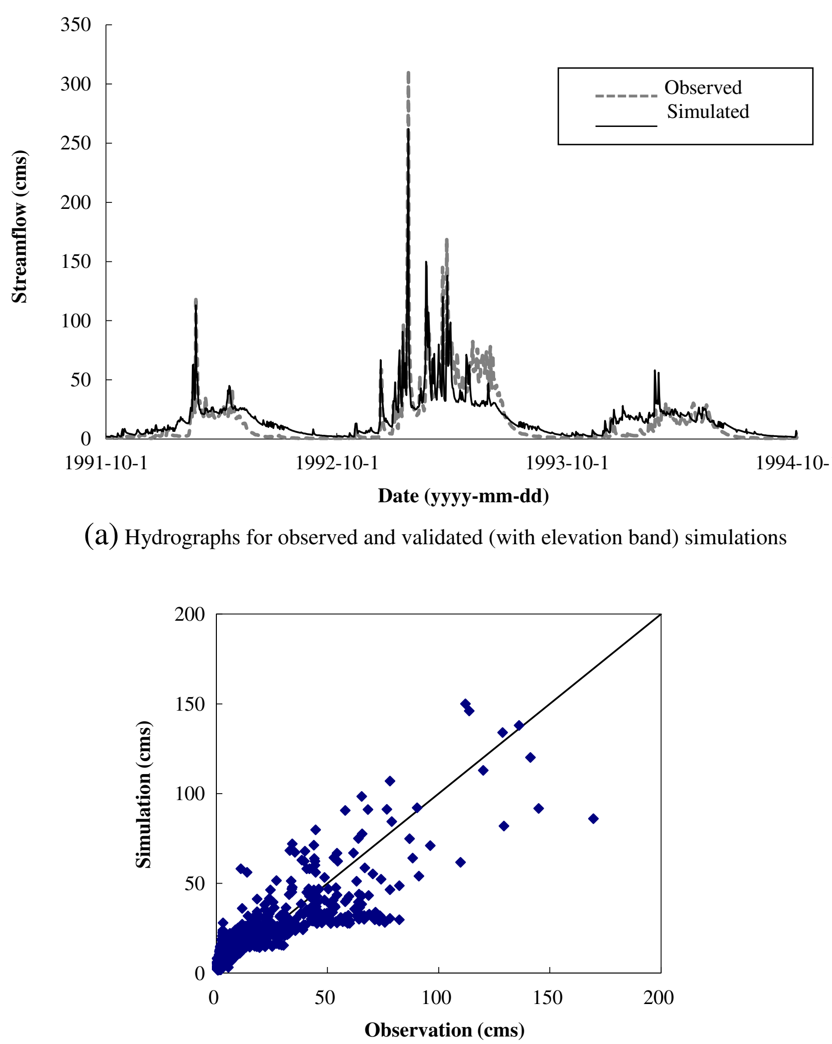
Figure 4. Validated model without elevation band. (**a**) Hydrographs for observed and validated (with elevation band) simulations. (**b**) Scatter plots with 1:1 line.

(TIMP) (Wang and Melesse 2005). Hence, this study adjusted SMFMX (from 3 to 4.5), SMFMN (from 3 to 4.5), and TIMP (from 0.5 to 1) during auto-calibration process. Upon completion of the auto-calibration, the simulation result in figure 3 exhibits much improved performance from statistical standpoint. See table 5 for the results of the simulation in terms of E_{NS}, RMSE, and R^2. As noted in table 5, validation(b) associated with the elevation band exhibits the best results in simulation in terms of all three performance statistics.

5. Model validation

After the calibration, the model is validated with and without considering the elevation band named validation(a) and validation(b). As mentioned earlier, the orographic effects of a mountainous watershed are relevant to elevation changes whereby temperature and precipitation contours along the slopes are determined (Hartman *et al.* 1999). According to Hartman *et al.* (1999) and Fontaine *et al.* (2002), spatial and temporal variations in hydrologic processes associated with elevation changes can be explained by using elevation bands. In this study, the elevation bands are spaced at five equal intervals as shown in table 4.

Next, temperature and precipitation lapse rates are used to relate temperature and precipitation changes to each elevation band. Precipitation data from seven NOAA climate stations and temperature measurements from six NOAA climate stations around the North Fork American River basin were used to compute the temperature and precipitation lapse rates. The relationship between mean annual temperature and station elevation developed by Fontaine *et al.* (2002) is used to compute temperature lapse rate. The mean annual temperature is calculated based on monthly NCDC data for the simulation period. The same process is



(a) Hydrographs for observed and validated (with elevation band) simulations

(b) Scatter plots with 1:1 line

Figure 5. Validated model with elevation band.

followed for the precipitation lapse rate. Subwatershed temperatures and precipitation are adjusted within each elevation band based on the difference between the elevation of the subwatershed meteorological station and each elevation band multiplied by the lapse rate (Fontaine *et al.* 2002). Equations (3 and 4) are used to adjust temperature and precipitation in accordance with the elevation band.

$$T_B = T + (Z_B - Z)\, dT/dZ \tag{3}$$

$$P_B = P + (Z_B - Z)\, dP/dZ \tag{4}$$

where T_B and P_B are adjusted temperature and precipitation by elevation band. Z is a meteorological station, and Z_B is the elevation band. In order to compute the snowmelt temperature on a date, it is necessary to use the temperature of a previous day and lag factors. The snow does not melt until the snowmelt temperature exceeds the subwatershed value. Equation (5) is used to compute the snowmelt temperature.

$$T_t^{\text{Snow}} = T_{(t-1)}^{\text{Snow}} - \left[T_{(t-1)}^{\text{Snow}} - L^{\text{Snow}}\right] + \left[T_{\text{Ave}} \times L^{\text{Snow}}\right], \tag{5}$$

where T_t^{Snow} is the current snowmelt temperature, T_{t-1}^{Snow} is snowmelt temperature of the previous day, L^{Snow} is snow temperature lag factor, and T_{Ave} is the current mean air temperature.

The results of validation without elevation band and validation with elevation band are shown in figures 4 and 5, respectively. In both figures, the solid line represents observed data, and the dashed line shows simulated result. Overall, both results are acceptable in terms of three statistics as noted in table 5. However, figure 5 shows better performance in simulation, i.e., 11.6%, 13.6%, and 9.72% improvement in terms of E_{NS}, RMSE, and R^2, respectively. Validation(b) not only represents peaks and low flows with acceptable accuracy, but it also exhibits adequate lag time. In addition to the improvement from statistical standpoint, the total water balance in model simulation shows just 52.39 mm difference over the 3-year period compared to the observed runoff depth. These results substantiate the effects of temperature and precipitation lapse rates associated with the elevation bands in mountainous watersheds, which agree with the results of other studies (Fontaine *et al.* 2002; Whitaker *et al.* 2002; Hunsaker *et al.* 2012).

6. Conclusions

This study simulated the orographic effects and temperature changes on long-term precipitation in North Fork American River basin where spatial variations of precipitation are observed in accordance with changes in elevation. The SWAT was used to incorporate the snowmelt-runoff mechanism into simulation. Over the course of simulation, several snowmelt-related parameters were calibrated and adjusted on the basis of previous studies. Snowmelt-related parameters were analysed during simulation in order to explore the effects of snowmelt and temperature. Lastly, two validation schemes were analysed: validation without considering elevation band and validation with considering the elevation band for precipitation and temperature inputs.

Note that this study has a limitation and an assumption in modelling the snowmelt mechanism. The SWE method could not be used in modelling the snowmelt mechanism in the study area. If there were enough precipitation data, the SWE method should be a logical approach to incorporate the snowmelt mechanism in modelling. This study, however, encountered large amount of missing data when the SWE method was used in simulation. Also, it is assumed that the addition of elevation bands do not affect the other previously calibrated parameters. Thus, once calibrated parameters do not have to be recalibrated during the modelling. With this underlying assumption, this study came to the following conclusions.

The snowmelt-runoff model associated with the elevation band exhibits better results in terms of E_{NS}, R^2, and RMSE. The model with the elevation band well represents peaks and low flows and shows adequate lag time. In addition to the improved statistics, the total water balance in model simulation shows only minimal difference from the observed runoff depth. These clearly explain the effects of temperature and precipitation lapse rates

Table 5. *Simulation results.*

Simulation	E_{NS}	RMSE (m^3/s)	R^2	Runoff depth (mm)
First run	−2.02	41.85	0.23	1926.36
Calibration	0.64	14.47	0.64	1591.33
Validation without elevation band	0.69	13.56	0.72	1651.43
Validation with elevation band	0.77	11.72	0.79	1611.96

associated with the elevation bands in the mountainous river watershed. The result of this study suggests that snowmelt effected on runoff with the elevation band in SWAT modelling in a mountainous watershed. However, since the simulation without the elevation band have also shown an acceptable result, snowmelt-related parameters in SWAT should be considered forsimulation.

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