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Predicting natural streamflows in regulated snowmelt-driven watersheds using regionalization methods

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Abstract

Predicting streamflows in snow-fed watersheds in the Western United States is important for water allocation. Since many of these watersheds are heavily regulated through canal networks and reservoirs, predicting expected natural flows and therefore water availability under limited data is always a challenge. This study investigates the applicability of the flow duration curve (FDC) method for predicting natural flows in gauged and ungauged snow-fed watersheds. Point snow observations, air temperature, precipitation, and snow water equivalent, are used to simulate snowmelt process with SNOW-17 model and extended to streamflow generation by a FDC method with modified current precipitation index. For regulated (ungauged) watersheds, a parametric regional FDC method is applied to reconstruct natural flow. For comparison, a simplified Tank Model is used as well. The proximity regionalization method is used to generate streamflow using the Tank Model in ungauged watersheds. The results show that the FDC method can produce acceptable natural flow estimates in both gauged and ungauged watersheds under data limited conditions. The performance of the FDC method is better in watersheds with relatively low evapotranspiration (ET). Multiple donor data sets including current precipitation index are recommended to reduce uncertainty of the regional FDC method for ungauged watersheds. In spite of its simplicity, the FDC method can perform better than the Tank Model under minimal data availability.

1 Introduction

Snow accounts for a significant portion of precipitation in the mountainous Western United States and snowmelt plays an important role in forecasting streamflow (Serreze et al., 1999). Extreme amounts of snowfall can result in a flood in the melting season, and sometimes snow accumulation alleviates drought by natural redistribution of precipitation in a high water demand period. In such regions, snowmelt controls the hydrologic processes and water relevant activities such as irrigation. Therefore, reliable prediction of snowmelt is crucial for water resources planning and management (He et al., 2011; Mizukami et al., 2011; Singh and Singh, 2001).

Traditionally, the snowmelt process is predicted by physical or conceptual models and both approaches use the energy budget of the snowpack. The only difference between these methods is whether physical processes are implicitly parameterized or not. Physical models (e.g. Anderson, 1976; Leavesley et al., 1987; Tarboton and Luce, 1996; Walter et al., 2005) use the direct energy budget at the surface of snowpack whereas conceptual models (e.g. Anderson, 2006; Albert and Krajeski, 1998; Neitsch et al., 2001) parameterize the snowmelt process with a temperature index (melt depth per degree day). Due to this parameterization, conceptual models require less input data than physical models, but have more parameters to be calibrated.

Conceptual models are frequently combined with deterministic runoff models to predict streamflows in snow-fed watersheds. Typically, conceptual models have good performance in spite of their simplicity (Anderson, 2006; Hock, 2003). To generate streamflow in snow-fed watersheds, commonly used models are SSARR (Cundy and Brooks, 1981), PRMS (Leavesley et al., 1983), NWSRFS (Larson, 2002), UBC (Quick and Pipes, 1976), CEQUEAU (Morin, 2002), HBV (Bergström, 1976), SRM (Martinec, 1975), TANK (Sugawara, 1995), and among others. These models can also be used for the simulation of streamflow using appropriate rainfall–runoff relationships.

However, deterministic models are faced with several difficulties in simulating snowmelt runoff due to the high data requirement. For example, an important input for modeling snowmelt runoff is snow cover area which cannot be readily measured through point observations. Most runoff simulations require daily estimates of snow cover areas which may not be available. Although remotely sensed images can estimate snow cover areas with good precision (Martinec et al., 2008), image processing requires significant effort and time. For these reasons, a classical snow depletion curve (a relationship between snow cover and depth) is still used to parameterize the snow cover area in runoff models. Also, it is recommended to divide the area to sub-areas even if the hydrologic model is not distributed (Martinec, 2008) since snow-fed watersheds are located at high elevations with significant elevation variability. However, such partitioning of a large watershed to smaller regions increases the input data requirements irrespective of the modeling approach.

As an alternate approach, linking point snow observations to streamflow can be a pragmatic option. A common statistical approach for simple simulation of streamflow is the Flow Duration Curve (FDC) method. A FDC gives a summary of streamflow variation and represents the relationship between streamflow and its exceedence probability (Vogel and Fennessey, 1994). For streamflow generation, one or multiple sets of donor streamflow data are transferred to a target station by corresponding exceedence probability of the donor sets with that of the target. A number of variations of the FDC method have been used for generation of daily streamflow data. Hughes and Smakhtin (1996), for instance, suggested a FDC method with a nonlinear spatial interpolation method to extend observed flow data. Smakhtin and Masse (2000) developed a variation of the FDC method to generate streamflow using rainfall observations as donor sets rather than streamflow data. Despite numerous applications of the FDC method, there is still no good approach using the FDC method to generate daily streamflow from point snow observations. Given the simplicity of the FDC method, a suitable approach using the FDC method to predict snowmelt-driven runoff using point observations will be practical and cost efficient due to the reduced data needs. For streamflow generation, at least one donor data set and the FDC of the target station are required. If the target station is ungauged, a regional FDC can estimate the FDC of the target station. The regional FDC is generally developed using the relationships between selected percentile flows in gauged FDCs and climatic or physical properties of the watersheds. Thus, the regional FDC estimates the unknown FDC of an ungauged watershed only with its physical properties. Many regional FDC methods have been proposed for generating streamflow at ungauged watersheds. Shu and Ouarda (2012) categorized the regional FDC methods as a statistical approach (e.g. Singh et al., 2001; Claps et al., 2005), a parametric approach (e.g. Yu et al., 2002; Mohamoud, 2008), and a graphical approach (e.g. Smakhtin et al., 1997). Statistical approaches define the relationship between the parameters of a frequency distribution and the corresponding physical or climatic characteristics. Parametric approaches identify parameters of analytical equations of the regional FDC method through regression analysis with physical and climatic characteristics. Graphical methods use a non-parametric standardized gauged FDC in a region rather than estimating the parameters using statistical or parametric approaches (Castellarin et al., 2004).

The regional FDC can be used not only for generating streamflow in ungauged watersheds, but also for reconstructing natural flows of watersheds regulated by reservoir operations, river diversions and other human activities. Smakhtin (1999), for example, evaluated the impact of reservoir operations by comparing between regulated outflows from a reservoir and natural flow estimated by a regional FDC. In the Western United States, the prior appropriation doctrine, the water right of “first in time, first in right,” has produced many river basins with impaired streamflow observations. These impairments are particularly significant in watersheds with high aridity, low precipitation, and relatively large water demands. Given the high water demands in these watersheds especially during the growing season starting in early spring, a good estimate of water availability in a given year is crucial to help effective water allocation for that year. However, a number of data sets such as volumes of river diversions and reservoir operation rules are necessary to estimate the water availability to fit simulated flows to the impaired streamflow observations directly. Indeed, combined effect of such regulations and natural hydrologic processes on the impaired streamflow is sometimes too complex to be modeled simultaneously. The regional FDC method, on the other hand, can be used to estimate the amount of water under natural flow conditions using minimal data. Even though the regional FDC method cannot simulate the individual streamflow pattern in a watershed such as direct runoff, infiltration and baseflow, it can produce approximate estimates of streamflow which can help water managers. Also, the difference between natural flows reconstructed by the regional FDC and the impaired streamflow observations can indicate the combined effects of reservoir operations, river diversions, and other human-driven activities. Thus, the effect of regulation in a watershed can be approximately evaluated from this comparison.

As discussed earlier, prior studies focused on predicting streamflows in natural and managed watersheds under typical rainfall–runoff conditions and not under snowmelt-driven streamflow generation modes. Therefore the goals of this work are twofold: (a) to assess the applicability of the FDC method and a simple lumped hydrologic model in conjunction with a conceptual snowmelt model to predict streamflows in a semi-arid snow-fed river basin, and (b) to assess the possibility of extending the work through regionalization to predict natural streamflows in regulated watersheds to determine water availability. In this work, a modified approach to the FDC method for streamflow generation from rainfall observations (Smakhtin and Masse, 2000) is proposed. The simplified SNOW-17 model is used here with point observations of snow to estimate snowmelt discharge required by the FDC method and the lumped model. Also, a parametric regional FDC method is applied for the reconstruction of natural flows and a proximity based regionalization approach for the lumped model is used for comparison with the regional FDC. By comparing with impaired streamflows and observed managed flows, water use in a watershed is estimated.

2 Methodology

2.1 SNOW-17 snowmelt model

This study uses SNOW-17 as the snowmelt model which has been used for river forecasting by the National Weather Service (NWS). SNOW-17 is a single-layered, conceptual snowmelt model. This model estimates snow water equivalent (SWE) and snowmelt depth as outputs. Input data required are precipitation and air temperature only. Although the original SNOW-17 model has 10 parameters for point-scale simulation, this study used the simplified model similar to Raleigh and Lundquist (2012). For simplification, temperature for dividing rainfall and snowfall (PXTEMP), base temperature for non-rain melt (MBASE), and the liquid water holding capacity (PLWHC) are assumed at typical values of 1.5 °C, 0 °C, and 5 %, respectively. Rain on snowmelt and daily melt at the snow–soil interface are deactivated since these contribute minimally to the energy budget of the snowmelt process (Raleigh and Lundquist, 2012; Walter et al., 2005). The simplified version has only five parameters, which are SCF, MFMAX, MFMIN, NMF, and TIPM. SCF is a multiplying factor to adjust new snow amounts. MFMAX and MFMIN are the maximum and minimum melting factors to calculate melting depths. NMF and TIPM are parameters for simulating energy exchange when there is no snow melt. A detailed description of the model is given by Anderson (2006). This study measures performance of SNOW-17 using Nash-Sutcliffe Efficiency (NSE) between observed and simulated SWE. The NSE is defined as:

$$\mathrm{NSE}_{\mathrm{SWE}} = 1 - \frac{\sum_{t=1}^{T}\left\{Q_{\mathrm{SWE}}(t) - \widehat{Q}_{\mathrm{SWE}}(t)\right\}^2}{\sum_{t=1}^{T}\left\{Q_{\mathrm{SWE}}(t) - \bar{Q}_{\mathrm{SWE}}\right\}^2} \tag{1}$$

where $Q_{\mathrm{SWE}}(t)$ and $\widehat{Q}_{\mathrm{SWE}}(t)$ are observed and simulated SWE's (mm) at time t, respectively, $\bar{Q}_{\mathrm{SWE}}$ is the mean observed SWE (mm), and T is the number of observations.

2.2 Modified FDC method with precipitation index

The FDC method is a non-parametric probability density function representing the relationship between magnitude of streamflow and its exceedence probability. The FDC method is typically used to generate daily streamflow at a station from highly correlating donor streamflow data sets with the target station. A drawback of this approach is that streamflow generation is dependent on the availability of the donor data sets. Hence, in a region with a low density of stream gauging stations, the FDC method may face the difficulty of not having adequate data.

Smakhtin and Masse (2000) developed a modified FDC method with a precipitation index to overcome the limited availability of donor data sets. Their method includes transforming the time-series of precipitation into an index having similar properties to streamflow data. The transformation is to avoid zero values in precipitation data caused by intermittency of precipitation events and will therefore produce a different shape of duration curve than typically expected. The duration curve of the transformed precipitation can indicate the exceedence probability at the outlet which determines the magnitude of streamflow.

This study uses the same concept with following modifications. First, the outflow depth simulated by SNOW-17 is used for constructing the FDC instead of precipitation data to represent the snowmelt process. Second, a constant recession coefficient is applied for the calculation of precipitation index of Smakhtin and Masse (2000), but different coefficients are used to represent different hydrologic responses of rainfall and snowmelt to streamflow. The modified approach is given below.

The current precipitation index at time t, $I_{\mathrm{CP}}(t)$, in mm is defined in the original work as,

$$I_{\mathrm{CP}}(t) = k \cdot I_{\mathrm{CP}}(t-1) \cdot \Delta t + P(t) \tag{2}$$

where k is the recession coefficient (d^{-1}), $P(t)$ is precipitation at time t(mm), and Δt is the time interval (d). Recession coefficient, k, represents the similar concept as the baseflow recession coefficient and needs to be calibrated. According to previous studies, k varies from $0.85\,\mathrm{d}^{-1}$ to $0.98\,\mathrm{d}^{-1}$ (Linsley et al., 1982; Fedora and Beschta, 1989). In addition, the initial value of I_{CP} can be assumed as the long term mean daily precipitation because of the fast convergence of calculations (Smakhtin and Masse, 2000).

To consider the snowmelt process in this study, outflow calculated by SNOW-17 is divided into two time-series. Time-series of snowmelt depth and rainfall depth are separated based on the existence of snow cover (when SWE > 0). It is important to stipulate different recession coefficients for snowmelt and rainfall processes given the different times scales of these processes for generating streamflow (DeWalle and Rango, 2008).

Finally, two indices are summed for simulating I_{CP}. Hence, the $I_{CP}(t)$ is redefined as

$$\begin{aligned} I_{CP}(t) &= I_{CS}(t) + I_{CR}(t) \\ I_{CS}(t) &= k_S \cdot I_{CS}(t-1) \cdot \Delta t + S(t) \qquad (3) \\ I_{CR}(t) &= k_R \cdot I_{CR}(t-1) \cdot \Delta t + R(t) \end{aligned}$$

where $I_{CS}(t)$ is the current snowmelt index (mm) at time t, $S(t)$ is the snowmelt depth (mm) at time t, $I_{CR}(t)$ is the current rainfall index (mm) at time t, $R(t)$ is the rainfall depth (mm) at time t, k_S and k_R are recession coefficients (d^{-1}) for snowmelt and rainfall, respectively. In this study, k_S and k_R are selected by values showing maximum correlation between I_{CP} and observed streamflow data. Figure 1 depicts the proposed FDC method used in this work.

The selection of a snow observation station when multiple stations are present in a watershed is based on high correlation between calculated I_{CP} and observed streamflow. Although Smaktin and Masse (2000) commented that the effect of weights in the case of multiple stations was not a significant factor in their original FDC method with the precipitation index, a high correlation between I_{CP} and streamflow supports better performance in the generation of streamflow because of the significant climatic variation of snow-fed watersheds located in high elevation regions.

2.3 Simplified tank model

This study uses the simplified Tank Model proposed by Cooper et al. (2007) to compare the performance under conditions of similar and limited data availability. The simplified Tank Model reduces the number of parameters of the original Tank Model (Sugawara, 1995) to help minimizing over-parameterization when the Tank Model is combined with the snowmelt model. This simplified Tank Model shown in Fig. 2 has two vertical layers with a secondary soil moisture layer in the upper tank. This study does not consider the secondary soil moisture layer because it is not sensitive to runoff simulation (Cooper et al., 2007). The combined model has 12 parameters (5 for snowmelt, 7 for runoff).

The model produces several modes of response representing the different conditions that may prevail in the watershed. The upper tank has a non-linear response in the rainfall–runoff process because of its multiple horizontal outlets whereas the lower tank has a linear response. There are three thresholds to determine the four modes of hydrologic response, which are H_S, H_1, and H_2. H_S represents the soil moisture holding capacity (mm). H_1 and H_2 represent lower and upper thresholds for generating surface runoff (mm). The four modes are determined by the water depth of the upper tank with respect to the thresholds.

Mode 1: water depth in the upper tank (mm), W_U, is below H_S such that no flows are generated in the upper tank. This mode represents a dry condition of the watershed and only baseflow discharges under this mode. Baseflow at time t (mm d^{-1}), $Q_B(t)$, from the lower linear tank is

$$Q_B(t) = K_L \cdot W_L(t) \tag{4}$$

where K_L is the coefficient of baseflow runoff (d^{-1}) and $W_L(t)$ is the water depth in the lower tank (mm) at time t.

Mode 2: W_U is higher than H_S, but lower than $H_S + H_1$. Infiltration starts in this mode while no surface flow is generated in the upper tank. Baseflow is calculated similar to Mode 1, and infiltration rate at time t (mm d^{-1}) is calculated by

$$f(t) = K_I \cdot \{W_U(t) - H_S\} \tag{5}$$

where K_I is the coefficient of infiltration (d^{-1}).

Mode 3: W_U is greater than $H_S + H_1$ and less than $H_S + H_1 + H_2$. From this mode, the watershed is saturated by snowmelt or rainfall. Infiltration occurs before surface flow. After infiltration, the first surface runoff (mm d^{-1}), Q_{S1}, is activated and given as

$$Q_{S1}(t) = K_{S1} \cdot \{W_U(t) - H_S - H_1 - f(t) \cdot \Delta t\} \tag{6}$$

where K_{S1} is the first coefficient of surface runoff (d^{-1}), and Δt is time interval (d). Baseflow is same as the other modes.

Mode 4: W_U is greater than $H_S + H_1 + H_2$. The second surface flow (mm d^{-1}), Q_{S2}, is activated after discharging infiltration and the first surface flow. $Q_{S2}(t)$ is given as

$$Q_{S2}(t) = K_{S2} \cdot \{W_U(t) - H_S - H_1 - H_2 - f(t) \cdot \Delta t - Q_{S1}(t) \cdot \Delta t\} \tag{7}$$

where K_{S2} is the second coefficient of surface runoff (d^{-1}).

The total runoff from the watershed (m^3 s^{-1}), $Q(t)$, is obtained by

$$Q(t) = \left[Q_B(t) + Q_{S1}(t) + Q_{S2}(t)\right] \cdot \frac{A_d}{86.4} \tag{8}$$

where A_d is the drainage area (km^2).

Water depth in the upper tank is updated as,

$$W_U(t+1) = W_U(t) + O(t) - E(t) - f(t) \cdot \Delta t - Q_{S1}(t) \cdot \Delta t - Q_{S2}(t) \cdot \Delta t \tag{9}$$

where $O(t)$ and $E(t)$ is snowmelt or rainfall depth (mm) calculated by SNOW-17 and daily evapotranspiration (mm) at time t, respectively. In this study, $E(t)$ is independently estimated by the method proposed by Anayah (2012) using the modified Complementary Method.

Lastly, the water depth in the lower tank is updated by

$$W_L(t+1) = W_L(t) + f(t) \cdot \Delta t - Q_B(t) \cdot \Delta t. \tag{10}$$

The parameters are optimized using genetic algorithm in MATLAB with the objective function of minimizing the sum of weighted residual shown as below.

$$\text{Minimize} \sum_{t=1}^{T} w(t) \cdot \left\{Q(t) - \widehat{Q}(t)\right\} \tag{11}$$

where $w(t)$ is weight (unitless) varying with magnitude of runoff data. This study uses a weight of 5 for the low runoff seasons and 1 for high runoff seasons to reduce the effect of possible errors in the high runoff seasons during optimization. $Q(t)$ and $\widehat{Q}(t)$ are observed and simulated streamflows ($\mathrm{m}^3\,\mathrm{s}^{-1}$), respectively, and T is the number of observations.

For simplicity of modeling, the Tank Model does not consider the snow cover area distribution and assumes the watershed is entirely covered by snow. This assumption is a simplification of reality, but the structure of the Tank Model is adequately flexible to be calibrated by streamflow observations. It has more parameters than the Snowmelt Runoff Model (SRM) with good applicability (Martinec et al., 2008). Inputs to the Tank Model, precipitation and temperature, are areal inputs rather than point observations. As mentioned earlier, the use of point observations only in a lumped model can produce bias due to the high climatic variations. It is therefore proposed to divide the watershed into several elevation zones with spatially averaged input data to minimize bias. This study uses PRISM data (PRISM Climate Group, 2012) representing the spatial variation of precipitation and air temperature throughout the United States. The method for adjusting point observations is explained later.

2.4 Regionalization

This study applies regionalization to simulate natural streamflows in regulated watersheds with impaired observations. A parametric approach is selected for constructing the regional FDC. The model proposed by Shu and Ouarda (2012) is used and given as

$$Q_\mathrm{P} = aV_1^\mathrm{b}V_2^\mathrm{c}V_3^\mathrm{d}\cdots \tag{12}$$

where Q_P is percentile flows, V_1, V_2, V_3, ... are selected physical or climatic descriptors, b, c, d, ... are model parameters, and a is the error term. The logarithmic transformation can help solve the model through linear regression. By step wise regression, independent variables are selected.

Meanwhile, the proximity based regionalization method is used for the Tank Model. In the case of deterministic models, regionalization of parameters for ungauged watersheds are categorized by three approaches (Peel and Blöschl, 2011): (a) regression analysis between individual parameters and watershed properties (e.g. Kim and Kaluarachchi, 2008; Gibbs et al., 2012); (b) parameter transfer based on spatial proximity (e.g. Vandewiele et al., 1991; Oudin et al., 2008), and (c) physical similarity (e.g. McIntyre et al., 2005; Oudin et al., 2008, 2010). Even if the performance of these three approaches is dependent on climatic conditions, performance and complexity of the model, and other factors, several studies concluded that the spatial proximity method is a good approach due to its better performance and simplicity (Oudin, 2008; Parajka et al., 2013). The rationale behind the proximity based methods is that parameter values that are relatively homogeneous within a region should have neighbors with similar behavior (Oudin et al., 2008). Multiple neighbors are recommended to reduce errors and the average of streamflows generated by each parameter set of neighbors is slightly better than the streamflow generated by the average parameter set of neighbors (Oudin et al., 2008). This study considers the proximity based regionalization for regulated watersheds. Multiple neighboring watersheds together with the average of streamflow generated by parameter sets of the neighbors are used for simulating natural flows of these watersheds.

3 Description of the study area and data

The study area is the Sevier River Basin located in South Central Utah and the details are given Fig. 3. The Sevier River Basin is a semi-arid basin with relatively high ET. Watersheds in or adjacent to the Sevier River Basin are dominantly fed by snowmelt from the high elevation region. Particularly, the Sevier River is significantly regulated by diversions and reservoir operations along the major channels for agricultural water use. Hence, a real-time streamflow monitoring system along to the main channel is operated by the Sevier River Water Users Association, but it is difficult to know the natural discharge from the regulated watersheds using this monitoring system.

This study used US Geological Survey (USGS) streamflow stations only representing natural streamflows for the FDC method and the Tank Model. Due to the lack of streamflow stations measuring natural flows, several adjacent watersheds are included as well. In addition, two USGS stations in the main Sevier River with significant impairments are selected for reconstructing natural flows using the regionalization methods. Precipitation, maximum and minimum air temperature, and SWE data from the SNOTEL stations operated by US Department of Agriculture (USDA) are used as inputs to the FDC method and the Tank Model. The details of the USGS stations and corresponding SNOTEL stations are given in Table 1 with data periods and watershed areas. Additionally, the records of canal diversions from the Utah Division of Water Right are used to compare streamflows generated by regionalization with actual river diversions. For the Tank Model, point SNOTEL data are adjusted to spatially averaged inputs using the PRISM database (PRISM Climate Group, 2012). The procedure is performed by a comparison between a pixel in a SNOTEL station and the areal average of pixels in a watershed using 30-arcsec annual normals from 1981 to 2010. The ratio of average of pixels to a pixel in the location of the point observation is multiplied by the point precipitation while the difference between them is added to the point temperature.

4 Results

4.1 SNOW-17 modeling

SNOW-17 is calibrated and verified by SWE observations at 12 SNOTEL stations using the computed SWE and outflow depths. Figure 4 illustrates the comparison between simulated and observed SWE and modeled outflow depth at three SNOTEL stations. The outflow depth is used to construct the FDC of I_{CP} while the SWE simulation is to calibrate parameters using the observed SWE data. The average NSE between simulated and observed SWE for calibration and verification are 0.942 (a range of 0.867 to 0.984) and 0.933 (a range of 0.793 to 0.967), respectively. The loss of NSE from calibration to verification is not significant and therefore the model is unlikely to be over-parameterized. However, there are certain biases which cannot be overcome by a conceptual model such as errors due to strong winds and dew-point temperature (Anderson, 1976). In other words, good calibration by SWE observations does not necessarily guarantee accurate simulation of outflow depth. One reason is the loss of SWE by winds or sublimation is not contributing to the melting depth even though there is a loss in the SWE observation. A conceptual model such as SNOW-17 should be used with caution at observation points due to the possibility for such errors. The effects of these error sources can be alleviated by the transformation of outflow depth to I_{CP} which has high correlation with streamflow observations.

4.2 Streamflow generation in gauged watersheds

The time-series of outflow depth from SNOW-17 is used to calculate I_{CP}. Since the rationale behind the FDC method is that exceedence probability of I_{CP} is same as that of streamflow, the data periods of both point snow observations and streamflow data should be same. In fact, I_{CP} calculation is mathematically equivalent to the computation of storage in a single linear reservoir such as the lower tank in the Tank Model. Hence, the hydrological meaning of I_{CP} is liquid water availability in a watershed with the assumption of a single linear reservoir. By the I_{CP} computation, the intermittent time-series of outflow depth is transformed to a smooth time-series.

The recession coefficient of snowmelt varies from 0.97 to 0.98 d^{-1} while for rainfall the range is 0.85 to 0.86 d^{-1}. These results show that snowmelt runoff is slowly changing during the year unlike rainfall runoff showing a relatively large fluctuation. The snowmelt depth cannot be more intermittent than the rainfall depth without a sudden increase in temperature. Furthermore, the snowmelt depth is statistically more clustered than the rainfall depth due to its seasonality. These observations result in relatively large recession coefficients for snowmelt runoff. In the study area, snowmelt runoff accounts for a large portion of streamflow and therefore the recession coefficient of snowmelt plays a major role in the high correlation between I_{CP} and streamflow. The recession coefficient of rainfall, on the other hand, has minimal sensitivity to the correlation between I_{CP} and streamflow. Hence, the correlation between I_{CP} and streamflow will not change significantly in the study area even in case that the recession coefficient for rainfall is same as that of snowmelt. However, if there are noticeable differences of rainfall runoff in streamflow observations, then the recession coefficient of rainfall is more important and sensitive. Particularly, the difference between snowmelt and rainfall runoffs can be crucial in the non-melting season, and therefore, the separation of recession coefficients is necessary for snow-fed watersheds with a relatively large portion of rainfall in precipitation.

Figure 5 shows the generated streamflow at several stations using the FDC method and the Tank Model. The performance of the FDC method and the Tank Model is summarized by NSE and Volume Error (VE) in Table 2. Typically, watersheds with good performance with the FDC method have good performance with the Tank Model too. Since both methods use linear coefficients for simulating streamflow, they perform well in watersheds with linear behavior and such watersheds are likely to have relatively homogenous climatic conditions. Watersheds with large variations of elevation such as Clear Creek do not have good performance with both methods. In other words, a high climatic variation can be a crucial source of error in the FDC method similar to lumped deterministic modeling. As expected, the climatic variation can be large as watershed area increases. The FDC method seems more sensitive to the scale of watershed than the Tank Model based on the underestimation of streamflow at Sevier River at Hatch (the largest watershed) by the FDC method.

4.3 Regional FDC for regulated watersheds

The FDC method and the Tank Model are upscaled to watersheds regulated by river diversions and reservoir operations to predict the natural flows at impaired streamflow stations. As mentioned earlier, the upscaling method is same as regionalization methods for ungauged watersheds. The description of two target watersheds used for this purpose is depicted in Fig. 6. As expected, natural flows from the agricultural area and canals in the two watersheds are significantly impaired by regulation. Streamflow observations at the stations of Sevier River near Kingston include river diversions while the diversions and reservoir operations are included in streamflow observations at Sevier River below San Pitch River near Gunnison (hereafter Sevier River near Gunnison). As depicted, both watersheds are divided into several sub-watersheds because the entire watersheds are too large to fall within the areas of gauged watersheds used for developing the regional FDCs. Hence, the sum of streamflows of each sub-watershed generated by regionalization is considered as the natural streamflow at each target station. In the case of Sevier River near Kingston, one sub-watershed is excluded since most flows from this watershed cannot contribute to streamflow at the station due to river diversions. Records of canal flows from the two watersheds are used for verification of simulated flows. Additionally, the outflow from the Rocky Ford Reservoir is included for comparison between simulated and observed flows at Sevier River near Gunnison.

As commented earlier, a step wise multiple regression analysis is used to identify the watershed physical and climatic properties which influence the percentile flows to determine the regional FDC of the study area. The candidate properties are listed in Table 3. The step wise regression in this study is implemented for each percentile flow in the MATLAB environment. A variable with largest significance among candidates is taken as an independent variable for the first step. Then, variables are added step by step based on the p value of F statistics. The selected variables for each percentile flow and the statistics of the regression model are given in Table 4.

As expected, the watershed area is included in every percentile flow as an independent variable. Larger watersheds naturally have greater percentile flows. Also, high flows are affected by elevation even if several high flows have potential ET (PET) as an independent variable while low flows are affected by a combination of river density, PET, and aridity. The study area is located in a mountainous region with high PET and therefore it is obvious that elevation and PET are major independent variables. In mountainous watersheds, the general tendency of precipitation and air temperature with elevation is to have positive and negative relationships, respectively. Thus, elevation can have the combined effect on both precipitation and air temperature thereby affecting streamflow. In addition, higher elevation means a greater depth of snow cover; therefore elevation has a positive relationship with high flows. Low flows, on the other hand, are strongly correlated with PET and aridity. In dry seasons, PET is crucial for streamflow than elevation. The Sevier River Basin does not have a permanent snow cover and the snow cover generally disappears after the peak flow. Hence, PET and aridity can be the most important variables after the completion of snowmelt. An interesting observation is that physical variables such as watershed slope are not selected as independent variables probably because the snowmelt process gives a stronger impact on streamflow than physical properties of the watersheds. As mentioned earlier, the temporal variation of snowmelt runoff is different from rainfall runoff since the climatic conditions can affect snowmelt runoff.

The values of R^2 in Table 4 show that streamflow forecasting with a regional FDC becomes uncertain as the exceedence probability increases. This indicates that linearity of PET on streamflow is weaker than other properties. Also, R^2 values reported here are smaller than the values from other regional FDC studies mostly from rain-fed watersheds (e.g. Mohamoud, 2008; Shu and Ouarda, 2012). A possible reason is the larger interaction among climatic properties (snowmelt) and physical properties (hydrologic processes) than in rain-fed watersheds. Consequently, regionalization for snow-fed watersheds may have more uncertainty than with rain-fed watersheds.

When using the regional FDC approach, I_{CP} is not necessarily used as the only donor data set to transfer exceedence probability to the target stations. In fact, the best donor data set is a data set which can show the best correlation with gauged streamflow at the target station. Given the lack of data, it is not possible to check the correlation between donor data sets and ungauged streamflow. Thus, one or multiple donor data sets close to the target station are typically used in regional FDC approaches. Shu and Ourda (2012) suggested using multiple sets of donor data to minimize uncertainty of using a single donor set. This study used two donor sets of streamflow observations as well as I_{CP} to generate streamflow in sub-watersheds. The recession coefficients are assumed to be 0.98 and 0.85 d^{-1} for snowmelt and rainfall, respectively.

Figure 7 illustrates the effect of multiple donor data sets on streamflow generation at Sevier River near Kingston. The gray-colored time-series show the sum of impaired streamflow and diversions. Hence, this time-series can be considered to be the reconstructed natural flow when diverted water is not returned to the stream. In fact, return flow always exists, but surface return flows are negligible during the water demanding season due to high water use efficiency. Also return flows through infiltration appear in the streams slowly. Thus, a comparison between the simulated streamflow and the reconstructed natural flow in a wet season can approximately measure the performance of each donor data set.

The closest donor data set to the target station (Sevier River near Kingston) is Sevier River at Hatch (USGS 10174500) while I_{CP} generated by SNOTEL data can be considered as the farthest donor data set. As a donor data set becomes closer to the target station, the difference between generated streamflow and the reconstructed natural streamflow is smaller as shown in Fig. 7. Therefore, proximity of the donor data sets is an important consideration. In spite of poorer performance compared to other donor sets, I_{CP} can capture climatic and physical characteristics of the watershed. Indeed, the use of multiple donor data sets typically enhances the performance of streamflow simulation using the regional FDC approaches. Thus, this study used the average of generated streamflows by three donor data sets as the natural streamflow at the target station.

Figure 8 shows generated streamflows by the regional FDC and the Tank Model with regionalized parameters at both target stations. In the case of Sevier River near Gunnison, the outflow from the Rocky Ford Reservoir is added to the streamflow observations. It can be easily recognized that these two watersheds are significantly regulated based on the irregular shapes of hydrographs. Natural flow at Sevier River near Kingston is affected by diversions only while streamflow at Sevier River near Gunnison is controlled by the combined effects of reservoir and diversions. The differences between the regional FDC method and the Tank Model for water volume are −2.89 and +8.43 % at Sevier River near Kingston and Sevier River near Gunnison, respectively. The difference in results seen here at Sevier River near Gunnison may be due to the high ET in the lower elevation of this station. Since this difference is small, it is difficult to assume that there is a large difference between the two approaches.

5 Discussions

In gauged watersheds, the Tank Model performs better than the FDC method in terms of NSE. One reason is the Tank Model is directly calibrated to streamflow observations while the FDC method matches the magnitudes of I_{CP} and streamflow based on an empirical probability density function. Particularly, the average NSE of the FDC method in the verification period is much smaller than the Tank Model. This is because a single extreme event can change the shape of the FDC. It is an important drawback when using the FDC method in streamflow generation. In other words, streamflow observations used in the FDC method are temporally less consistent than the relationship between forcing and runoff used in the Tank Model. To alleviate this drawback, monthly FDCs capturing the seasonal characteristics of streamflow can improve performance in regions with adequately long records of climatic and streamflow data (Smakhtin and Masse, 2000).

On the other hand, it is difficult to assume that the Tank Model performs better than the FDC method when using the VE estimates. Even watersheds such as the Salt Creek and Fish Creek with small NSE values have better performance in terms of VE. The results suggest that the average volume of runoff can be precise even if timing of streamflow generated by the FDC method is poor. This type of error in timing is likely to be originated from the temporal instability of the recession coefficients for I_{CP} calculations. Constant recession coefficients sometimes cannot follow the dynamic hydrologic response due to its simplicity. Streamflow generation by the FDC method is highly dependent on the variation of I_{CP}. Unfortunately, I_{CP} is not a streamflow observation, but an index mimicking the general behavior of streamflow observations. Hence, using I_{CP} sometimes can be the second option of FDC when donor streamflow data sets that are well correlated with the target station are available.

Another important factor affecting the performance of the FDC method is ET. Since the FDC method does not consider the effect of ET on I_{CP}, watersheds with high ET can produce more error than others. As depicted in Fig. 5, Vernon Creek with highest ET is among the gauged watersheds that have poor performance with the FDC method in terms of NSE. In watersheds with high ET, streamflow observations do not have fluctuations such as I_{CP} in a dry season since snowmelt or rainfall cannot effectively contribute to streamflow. A low correlation between I_{CP} and streamflow can happen because of the limited contribution of forcing so the FDC method is not recommended for high ET watersheds especially in the dry seasons. For such watersheds, the FDC method with good donor streamflow data or a well-developed deterministic model can be another option.

In short, the FDC method can be recommended for snow-fed watersheds with adequate homogeneity of climate and insignificant effect of ET on streamflow. Point snowmelt modeling, of course, should have adequate accuracy to generate streamflow. Using different FDCs for the 12 different months to capture seasonality of streamflow and I_{CP} can enhance performance of forecasting. The duration curves should be frequently updated to reflect the temporal variation. Without the burden of computational requirements, the FDC method can produce approximate streamflow estimates. Since only one point snow observation is used as a donor data set, data required by the FDC method are simply precipitation, air temperature, and SWE observations to calibrate the point snowmelt model. However, the FDC method provides approximate values of streamflow using the assumption of same exceedence probability between streamflow and I_{CP} from a point snow observation. If high accuracy of forecasting is necessary, other approaches such as physical models should be used.

In regulated watersheds, the simulated streamflows are higher than observed from April to October due to river diversions for agriculture except for year 2011 at Sevier

River near Gunnison. Sevier River near Gunnison is located below the intersection between the Sevier River and the San Pitch River, but it is difficult to know the streamflow from the San Pitch River on a regular basis. Streamflows from the San Pitch River is negligible in dry and normal years due to the high agricultural water demand in the San Pitch River Basin, but it cannot be neglected in a wet year such as 2011. Thus the observed streamflows at Sevier River near Gunnison can be somewhat greater than generated natural flows in a wet year as shown in Fig. 8b.

Conceptually, when the generated streamflow is greater than the observed flow, the difference indicates the volume of diversions. However, a similar difference can be assumed to represent the volume of return flow from the agricultural areas when the observation is greater than the generation. As depicted in Fig. 8a, streamflow not decaying from November to March (the period of no diversions) demonstrates that the return flows through infiltration affect streamflow continuously. Return flows may affect streamflow during the period of diversions, but it is difficult to estimate the impact due to the complexity of combined flow. Simply, a positive difference between the generated and observed flows in Fig. 8a indicates diversions including return flows whereas a negative difference indicates return flow on streamflow.

This study used observed diversions in the watersheds to validate the simulated natural streamflow. Most river diversions above Sevier River near Kingston are recorded for management purposes. Due to the high efficiency of water use in the agricultural area above this station, the effect of surface return flows may be small or negligible during the period of diversions. Even though the return flows through infiltration may affect streamflow, it is relatively small when compared to total diversions and streamflow during the period of diversions. If one assumes that there is no effect of return flows during the diversion season, the difference between simulated and observed flows can be considered to be the volume of diversions. Table 5 shows the sum of observed diversions in the main channel of the Sevier River above Sevier River near Kingston and the estimated volumes from the two methods. Although the Tank Model with regionalization seems more precise than the regional FDC, the estimated volume of diversions assumes no effect of return flows. Therefore it is difficult provide an assessment of the accuracy of estimated volumes in Table 5.

An important goal of this work of using regional approaches is to estimate the amount of water from streamflow without actual diversion data. In most of these situations, data are limited yet water managers require such information to better manage water demands. The results of this analysis especially from Table 5 show that the Tank Model with regionalization produces more stable predictions, but the regional FDC method can also produce estimates with comparable precision.

There are several limitations in the regional FDC method. For every regionalization approach including the regional FDC method, adequate streamflow observations are necessary to have good estimates. Parajka et al. (2013) commented that studies with more than 20 gauging stations have better and more stable performance with deterministic models. The regional FDC method is also sensitive to the number of gauging stations. Although the density of gauging stations is low in this study, gauged watersheds in the regional analysis should be adequate in terms of the watershed scale and climatic characteristics to minimize bias. As mentioned earlier, multiple donor data sets can also minimize errors caused by bias of a single donor set.

6 Conclusions

In this study, a conceptual snowmelt model, SNOW-17, using point snow observations is extended using a modified FDC method to simulate streamflows in the semi-arid and mountainous Sevier River Basin of Utah. The FDC method is later extended to simulate natural streamflows in regulated watersheds by incorporating a parametric regional FDC method. The FDC method can be a simple practical approach for streamflow generation for watersheds with limited data. The FDC method is compared with a simplified Tank Model under similar data availability to simulate streamflows and later extended via regionalization to estimate natural flows in regulated watersheds.

The results show that the FDC method can be a practical option for snow-fed watersheds with adequate homogeneity of climatic conditions. Of course, the performance of the snowmelt model is a prerequisite for good performance. With streamflow observations, I_{CP} can be correlated and can be a good donor data set without other neighboring streamflow observations. In spite of the simplicity of the FDC method, it can provide approximate estimates of natural flow in terms of water volume. High ET can result in error in the simulated streamflows since the FDC method does not consider the effect of ET. Heterogeneity of climatic conditions can also produce bias in the simulated streamflow. However, a lumped model such as the proposed Tank Model can also be affected by such errors. In such instances, the FDC method sometimes can simulate streamflows with better precision. Without the burden of parameter optimization and related computations of hydrologic processes, the FDC method can generate approximate streamflows with comparable precision to lumped modeling. For better performance, monthly FDCs capturing the seasonality of streamflow observations can be used instead of an annual FDC.

In the case of ungauged or regulated watersheds, a regional FDC should replace the gauged FDC, and multiple donor stations can improve the precision of streamflow predictions. In snow-fed watersheds, elevation is important to characterize percentile flows. High ET also results in high uncertainty of percentile flows especially for low flows. The difference between simulated streamflows of a regional FDC and a Tank Model with regionalization is not significant. When multiple donor stations are available, the FDC method can perform better than the Tank Model. When only using I_{CP} of the FDC method, uncertainty can be larger than the Tank Model. However, it is difficult confirm that the Tank Model performs better than the FDC method since the Tank Model is also regionalized from multiple gauged watersheds. In this work, the simulated natural flow is used to estimate the volume of river diversions in regulated watersheds with impaired streamflow observations. Both the regional FDC and the regionalization of the Tank Model estimated the approximate volumes of river diversions. Due to their similar performances, both estimation approaches can provide practical values under data limited conditions for water resources planning and management.

In short, the FDC method can be a practical method for the simulation of natural flows in both gauged and ungauged or regulated watersheds especially under limited data. However, the parameters of snowmelt modeling should be estimated using SWE observations as shown here. Other studies are necessary to determine the parameters of the snowmelt model for watersheds without SWE observations. Also, the difficulty of determining the recession coefficients for I_{CP} calculation in ungauged watersheds is another remaining issue since the typical values for gauged watersheds are assumed. The FDC approach used here can produce practical values of expected streamflows from point observations for watersheds with limited data.

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Table 1. Details of gauged watersheds and corresponding USGS and SNOTEL stations.

#	USGS Station	Gauged Watershed (River Name)	Area (km^2)	SNOTEL station	Data Period Calibration	Verification
1	10173450	Mammoth Creek	271.9	Castle Valley	2001–2006	2007–2011
2	10174500	Sevier River at Hatch	880.6	Midway Valley	2001–2006	2007–2011
3	10194200	Clear Creek	424.8	Kimberly Mine	2001–2006	2007–2011
4	10205030	Salina Creek	134.2	Pickle KEG	2001–2006	2007–2011
5	10215900	Manti Creek	68.4	Seeley Creek	2001–2006	2007–2011
6	10242000	Coal Creek	209.5	Webster Flat	2001–2006	2007–2011
7	10234500	Beaver River	235.7	Merchant Valley	2001–2006	2007–2011
8	10172700	Vernon Creek	64.7	Vernon Creek	2001–2006	2007–2011
9	10146000	Salt Creek	247.6	Payson R.S.	2001–2006	2007–2011
10	09310500	Fish Creek	155.7	Mammoth-Cottonwood	2001–2006	2007–2011
11	09326500	Ferron Creek	357.4	Buck Flat	2001–2006	2007–2011
12	09330500	Muddy Creek	271.9	Dill's Camp	2001–2006	2007–2011
13	09329050	Seven Mile Creek	62.2	Black Flat-U.M. CK	1992–1998	2008–2011

Table 2. Comparison between the FDC method and the Tank Model.

#	Gauged Watershed	NSE (Calibration/Verification) FDC	NSE (Calibration/Verification) Tank Model	VE (%)[*] (Calibration/Verification) FDC	VE (%)[*] (Calibration/Verification) Tank Model
1	Mammoth Creek	0.83/0.88	0.83/0.85	−1.1/4.4	7.1/16.4
2	Sevier River at Hatch	0.67/0.74	0.90/0.83	−27.2/−24.4	−12.4/−8.1
3	Clear Creek	0.63/−0.40	0.47/−0.10	1.4/5.7	−47.1/7.4
4	Salina Creek	0.53/0.50	0.60/0.58	−0.4/0.5	−1.7/17.7
5	Manti Creek	0.65/0.36	0.84/0.61	1.0/17.1	−20.4/−21.3
6	Coal Creek	0.87/0.55	0.90/0.42	−0.4/28.2	−14.0/15.2
7	Beaver River	0.84/0.82	0.90/0.80	−17.1/−14.1	−3.9/3.7
8	Vernon Creek	0.37/−1.03	0.75/0.48	0.9/−3.8	−8.1/−6.0
9	Salt Creek	0.55/−0.12	0.57/0.45	0.2/6.0	−3.7/−8.3
10	Fish Creek	0.81/−0.33	0.86/0.63	−1.2/25.3	0.9/3.8
11	Ferron Creek	0.91/0.87	0.85/0.81	−1.3/−4.0	−11.4/−0.8
12	Muddy Creek	0.31/−0.04	0.46/0.68	1.4/29.6	−25.2/29.8
13	Seven Mile Creek	0.66/0.67	0.74/0.73	2.1/3.0	−7.0/−6.3
	Average	0.66/0.27	0.74/0.60	−3.2/5.7	−11.3/3.3
	Maximum	0.91/0.88	0.90/0.85	2.1/29.6	7.1/29.8
	Minimum	0.31/−1.03	0.46/−0.10	−27.2/−24.4	−47.1/−21.3

[*] VE(%) = $\frac{\sum Q(t)-\sum \widehat{Q}(t)}{\sum Q(t)}$ × 100 where $Q(t)$ and $\widehat{Q}(t)$ are observed and simulated streamflows at time t, respectively.

Table 3. Candidate variables for multiple linear regression analysis.

Variable		Unit	Maximum	Mean	Minimum
Watershed Area	ARA	km^2	868.86	191.76	14.45
Longest Flow Length	LFL	km	66.28	24.68	6.28
Drainage Density	RD	km km^{-2}	0.40	0.29	0.19
Elongation Ratio	ELO	–	0.75	0.58	0.45
Watershed Slope	SLP	% rise	25.16	15.70	5.98
Forest Cover	FCV	%	100.00	72.06	36.72
Mean Elevation	ELE	m	2939.71	2610.41	2253.84
Annual Precipitation	PPT	mm	848.613	651.08	510.84
Annual Potential ET	PET	mm	1032.82	919.96	820.13
Aridity (PET/PPT)	ARD	mm mm^{-1}	2.22	1.52	1.07

Table 4. Selected variables and statistics of the regional FDC method.

Percentile flows	Selected Variables	R^2	p statistic
$Q_{0.1}$	ARA, ELE	0.757	0.0008
Q_1	ARA, PET	0.829	0.0001
Q_5	ARA, PET	0.848	0.0001
Q_{10}	ARA, PET	0.880	< 0.0001
Q_{20}	ARA, ELE	0.913	< 0.0001
Q_{30}	ARA, ELE	0.931	< 0.0001
Q_{40}	ARA, ELE	0.933	< 0.0001
Q_{50}	ARA, ELE	0.920	< 0.0001
Q_{60}	ARA, ELE	0.872	< 0.0001
Q_{70}	ARA, ARD	0.842	0.0001
Q_{80}	ARA, ARD	0.751	0.0010
Q_{90}	ARA, RD, PET, ARD	0.746	0.0165
Q_{95}	ARA, RD, PET, ARD	0.651	0.0532
Q_{99}	ARA, RD, PET, ARD	0.564	0.1173
$Q_{99.9}$	ARA, RD, PET, ARD	0.461	0.2399

Table 5. Estimated impairment and observed canal diversions, Sevier River near Kingston, April to September. The numbers within parentheses are percent difference from the observed volume.

Year	Estimated volume of diversion ($\times 10^6 m^3$) FDC	Tank	Observed volume of diversion ($\times 10^6 m^3$)
2008	95.68 (+21.3 %)	68.73 (−12.9 %)	78.88
2009	94.10 (+14.8 %)	61.30 (−25.2 %)	81.96
2010	120.77 (+63.4 %)	95.46 (+29.2 %)	73.92
2011	89.04 (−19.7 %)	131.97 (+19.0 %)	110.94

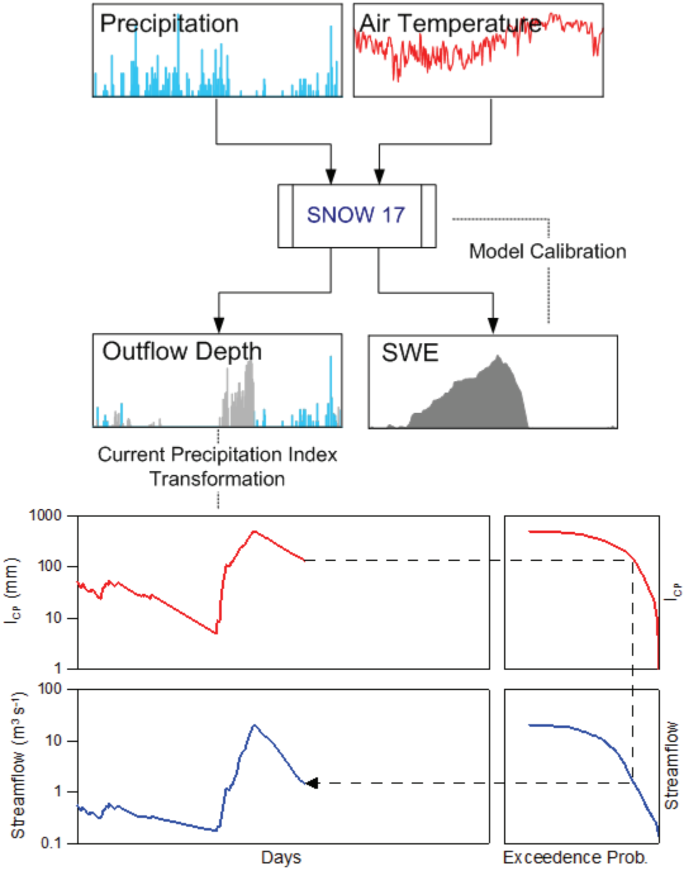

Fig. 1. Details of the proposed modeling approach with the FDC method and the SNOW-17 model.

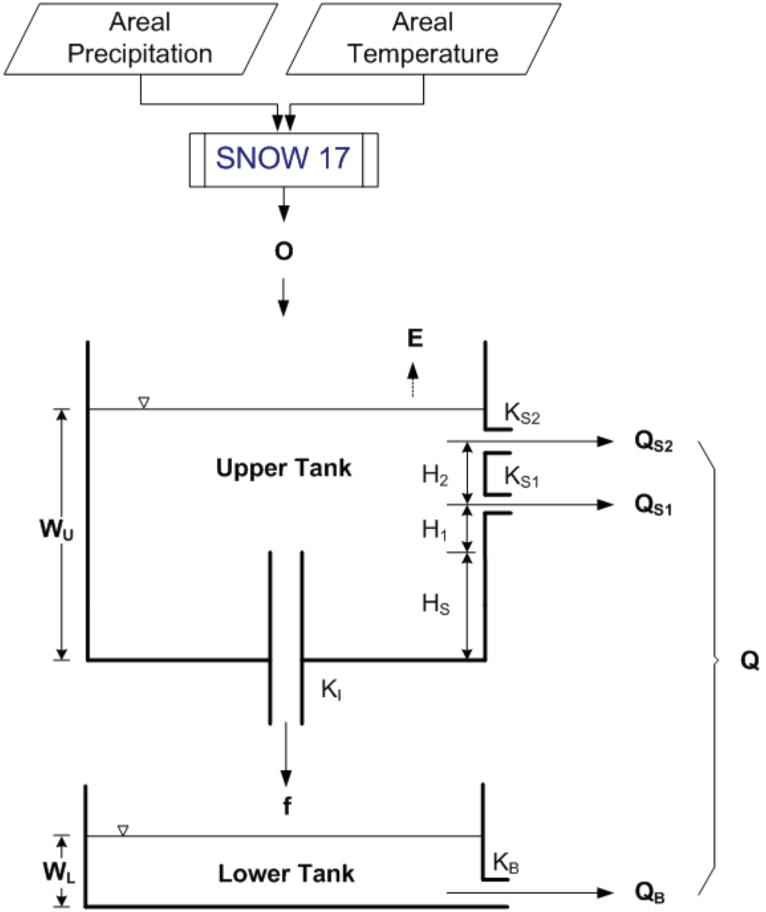

Fig. 2. Details of the proposed approach with theTank Model and SNOW-17.

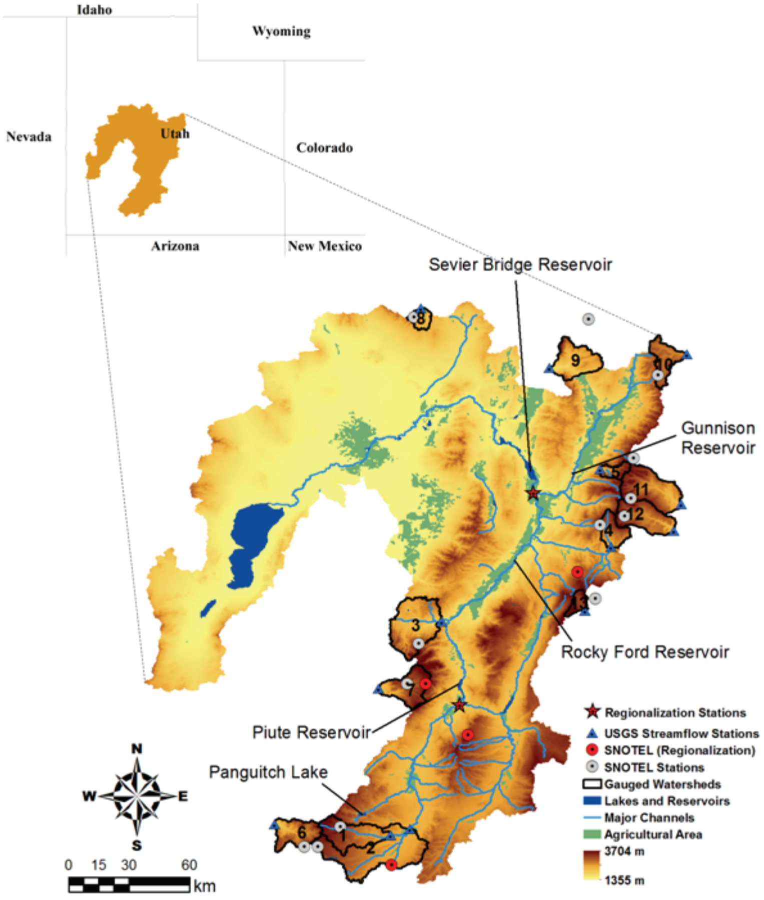

Fig. 3. Physical layout of the Sevier River Basin, Utah.

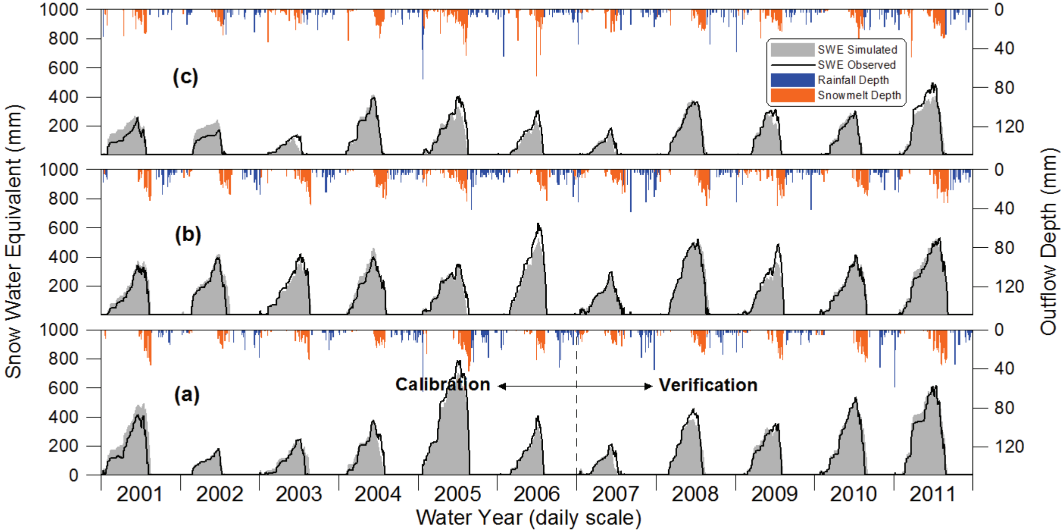

Fig. 4. Results from SNOW-17 at SNOTEL stations: **(a)** Castle Valley, **(b)** Pickle KEG, **(c)** Vernon Creek.

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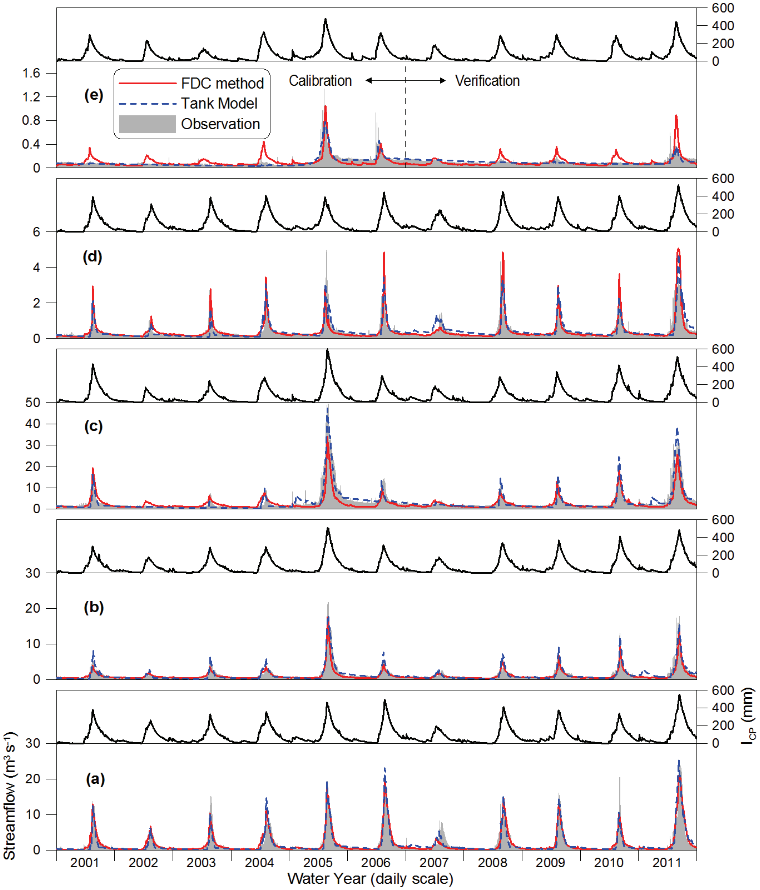

Fig. 5. Simulated streamflows with the FDC and the Tank Model: **(a)** Ferron Creek, **(b)** Beaver River, **(c)** Sever River at Hatch, **(d)** Salina Creek, and **(e)** Vernon Creek.

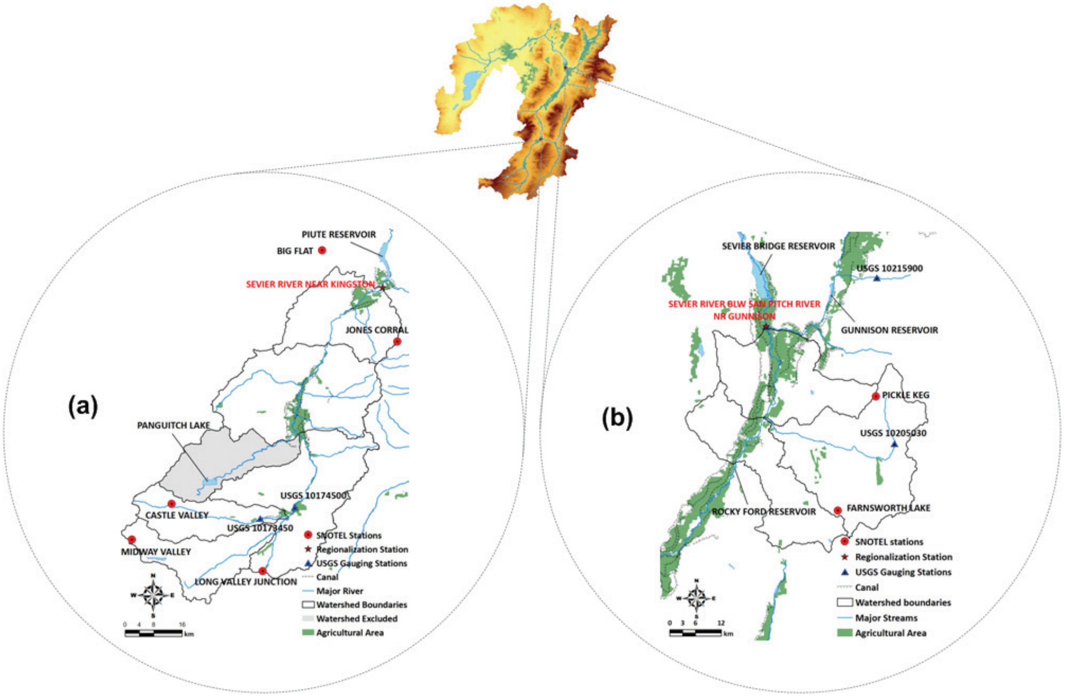

Fig. 6. Description of the target watersheds for regionalization: **(a)** Sevier River near Kingston, and **(b)** Sevier River below San Pitch River near Gunnison.

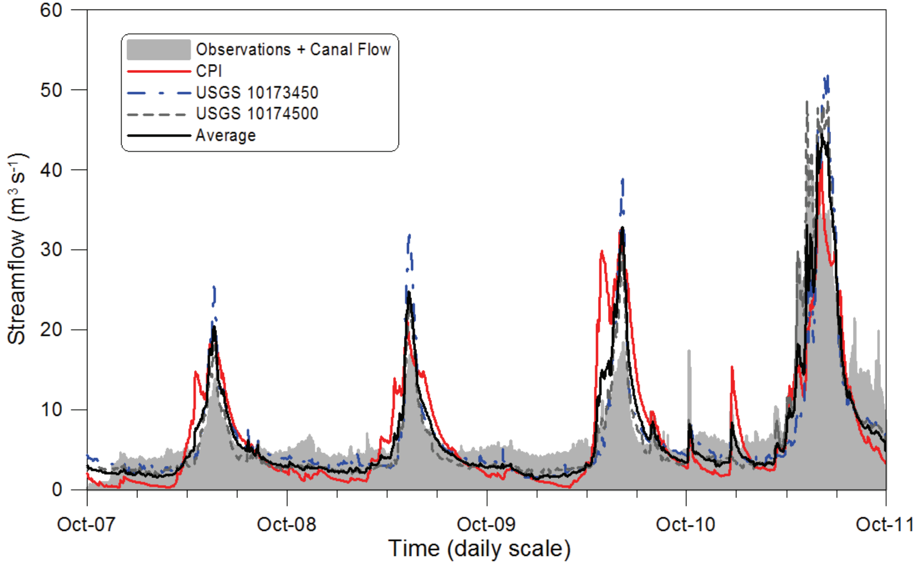

Fig. 7. Effect of donor data sets, USGS 10173450 and USGS 10174500, on streamflow estimation at Sevier River near Kingston.

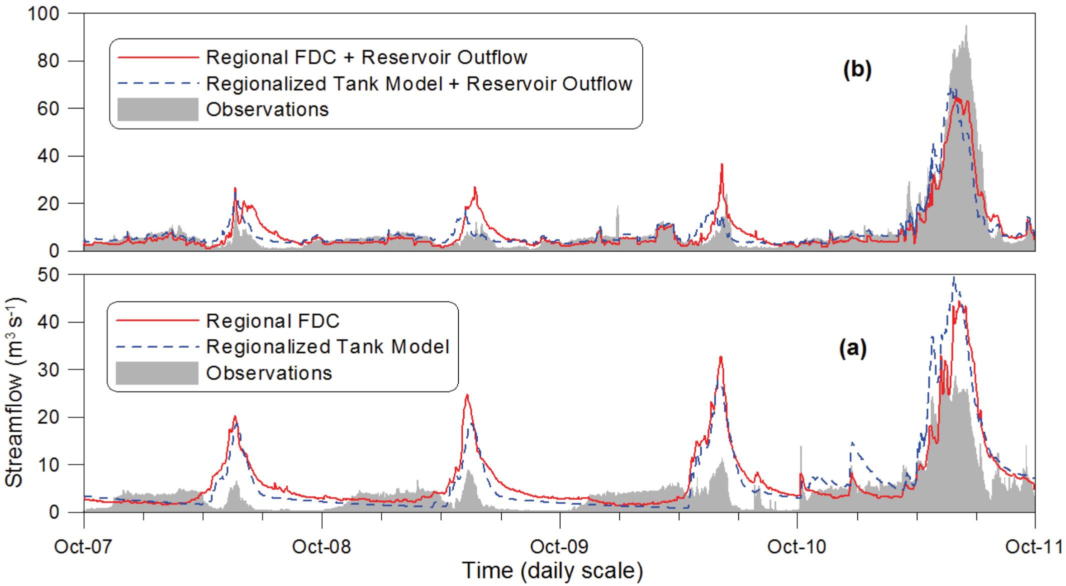

Fig. 8. Simulated streamflow in regulated watersheds: **(a)** Sevier River near Kingston, and **(b)** Sevier River below San Pitch River near Gunnison.