Hydrologic Analysis and Process-Based Modeling for the Upper Cache La Poudre Basin

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HYDROLOGIC ANALYSIS AND PROCESS-BASED MODELING FOR THE UPPER CACHE LA POUDRE BASIN

By

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COMPLETION REPORT

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Abstract:

The Cache la Poudre basin in northern Colorado provides water supplies to many agricultural and municipal users. In this study we analyzed sources of variability in the water yield produced in the upper Cache la Poudre basin above the river forecasting location. The primary objective of the research was to conduct a comprehensive hydrologic analysis that included investigation of (1) relations between snow variables and water yield, (2) spatial snow cover patterns during the melt season, and (3) hydrologic modeling approaches for exploring the sensitivity of river flow to variability in precipitation and temperature. Hydrologic analyses conducted for this project relied on precipitation, temperature, snow water equivalent (SWE), snow covered area (SCA) from the MODIS satellite sensor, and naturalized river flow during the snowmelt runoff season, which we defined as lasting from March-September. We also used these variables in conceptual hydrologic models that related changes in either SCA or SWE to the quantity of runoff generation in different elevation zones of the Cache la Poudre basin.

Analyses of the SCA illustrated spatial patterns in the snowpack for the basin. Results showed that during the past decade, elevations below approximately 2,700 m (8,900 ft) had seasonally intermittent snow cover, whereas elevations above around 3,000 m (9,800 ft) had seasonally persistent snow cover that lasted well into the spring. In a transitional snow cover zone between 2,700-3,000 m elevation, the timing of snow cover depletion during the spring correlated with the rising hydrograph in the Cache la Poudre River. Peak river flow occurred in May to early June, as the higher elevations with seasonally persistent snowpack were melting. SWE measurements in the basin were collected at two SNOTEL sites within this seasonally persistent snow zone. Peak SWE at these sites explained >60% of the variance in water yield for the Cache la Poudre; however the timing of peak SWE was highly variable from year to year, ranging from mid-March to early June.

Hydrologic modeling results for 2000-2009 indicated that on average 50% of the water yield for the upper Cache la Poudre was produced from the elevation zone between approximately 3,000-3,400 m, which is the elevation zone that includes the two SNOTEL sites. The transitional elevation zone (2,700-3,000 m) could also produce a large fraction of total water yield, up to 33% in 2003. In other years the water yield from this zone was much lower, down to a minimum of 2% in 2006. Model results also illustrated high sensitivity in water yield to spring temperature and precipitation. Results indicate that important sources of variability in water yield in the Cache la Poudre are (1) spring precipitation and temperature patterns, and (2) variability in the magnitude of snow accumulation and runoff production from the middle elevation snow transition zone.

Keywords:

Hydrologic modeling, Flow forecasting, Climate variability

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Justification of Work Performed

Colorado is strongly dependent on surface water resources, and the majority of surface runoff in the state's river basins comes from melting of the high elevation snowpack. To aid in water resource planning and management, the Natural Resources Conservation Service (NRCS) and other regional water management agencies issue seasonal flow forecasts. These forecasts are usually developed using statistical models that rely primarily on snow water equivalent measurements from snow telemetry (SNOTEL) sites. In the Cache la Poudre basin of northern Colorado, seasonal flow forecasts over-estimated water yield during most years from 2000-2007 (Figure 1). These forecasts prompted local water users to question whether some aspect of the hydrologic regime of the basin had changed in recent years.

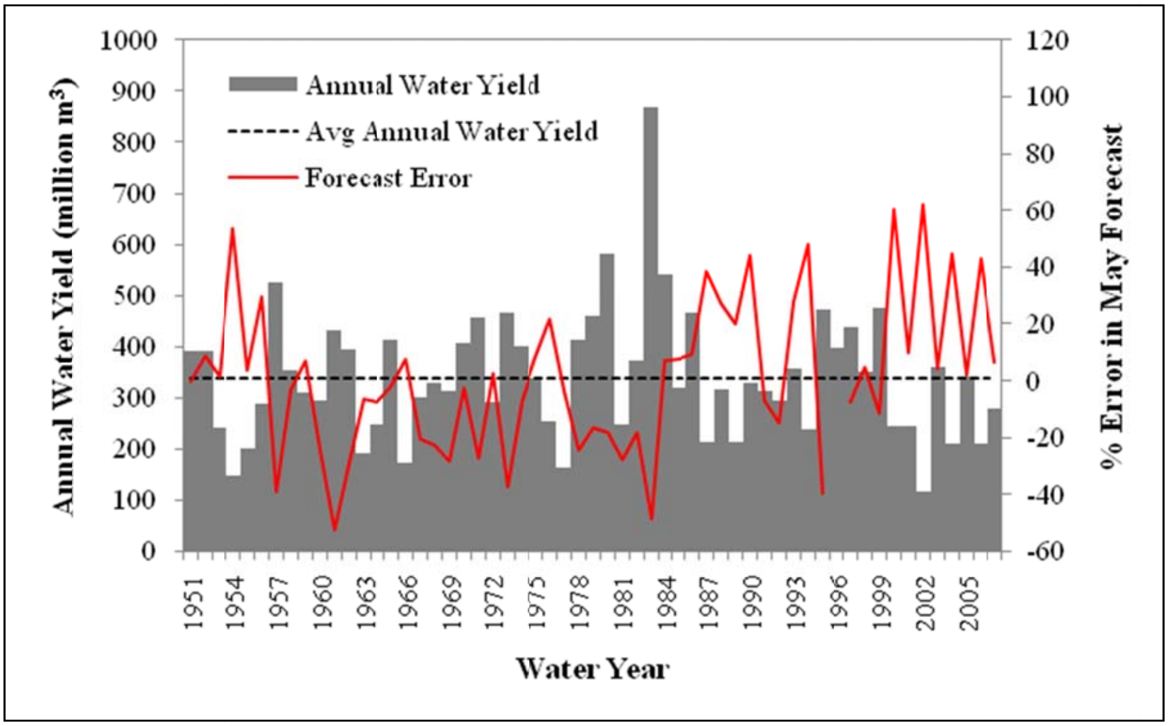

FIGURE 1. Naturalized annual water yield and NRCS May forecast error for the Cache la Poudre River at Canyon Mouth: WY 1951-2007.

The research reported herein represents an analysis of the sources of river flow variability in the Cache la Poudre basin, with an emphasis on testing the utility of satellite snow cover data for informing seasonal flow forecasts in the basin. The primary objective of the research was to conduct a comprehensive hydrologic analysis of the part of the Cache la Poudre basin upstream of the Canyon Mouth stream gauge, the flow forecasting location (Figure 2). Through this hydrologic analysis, we investigated (1) relations between snow variables and water yield, (2) spatial snow cover patterns during the melt season, and (3) hydrologic modeling approaches for exploring the sensitivity of river flow to variability in snowpack and temperature.

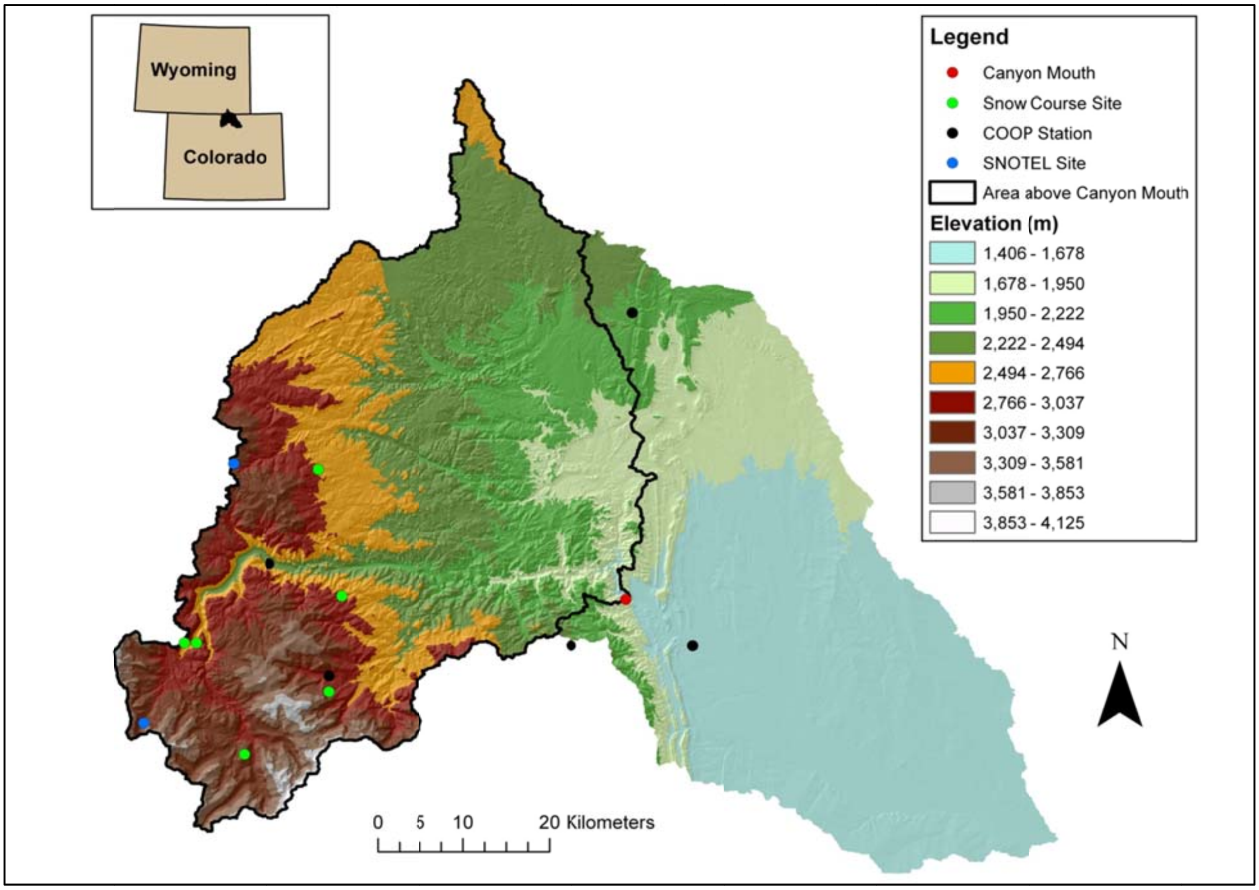

FIGURE 2. Location map for the Cache la Poudre basin with SNOTEL, meteorological (COOP) station, and stream gauge measurement locations, including the forecasting location at the Canyon Mouth.

Background

Basin description

The Cache la Poudre River is located in northern Colorado, with a small fraction of the basin in southern Wyoming (Figure 2). The river is used as a water source for both agriculture and municipal water users in the region. The Cache la Poudre basin covers an area of 4,824 km^2 (1,863 mi^2) and ranges in elevation from 1,406-4,125 m (4,613 – 13,533 ft). The fraction of the basin above the Canyon Mouth stream gauge is the focus of our study, and this part of the basin covers an area of 2,730 km^2 (1,054 mi^2), with a minimum elevation of 1,590 m (5,217 ft). Land cover in the basin includes tundra at high elevation, subalpine and montane coniferous forest at middle elevations, and grasslands at low elevations (Figure 3).

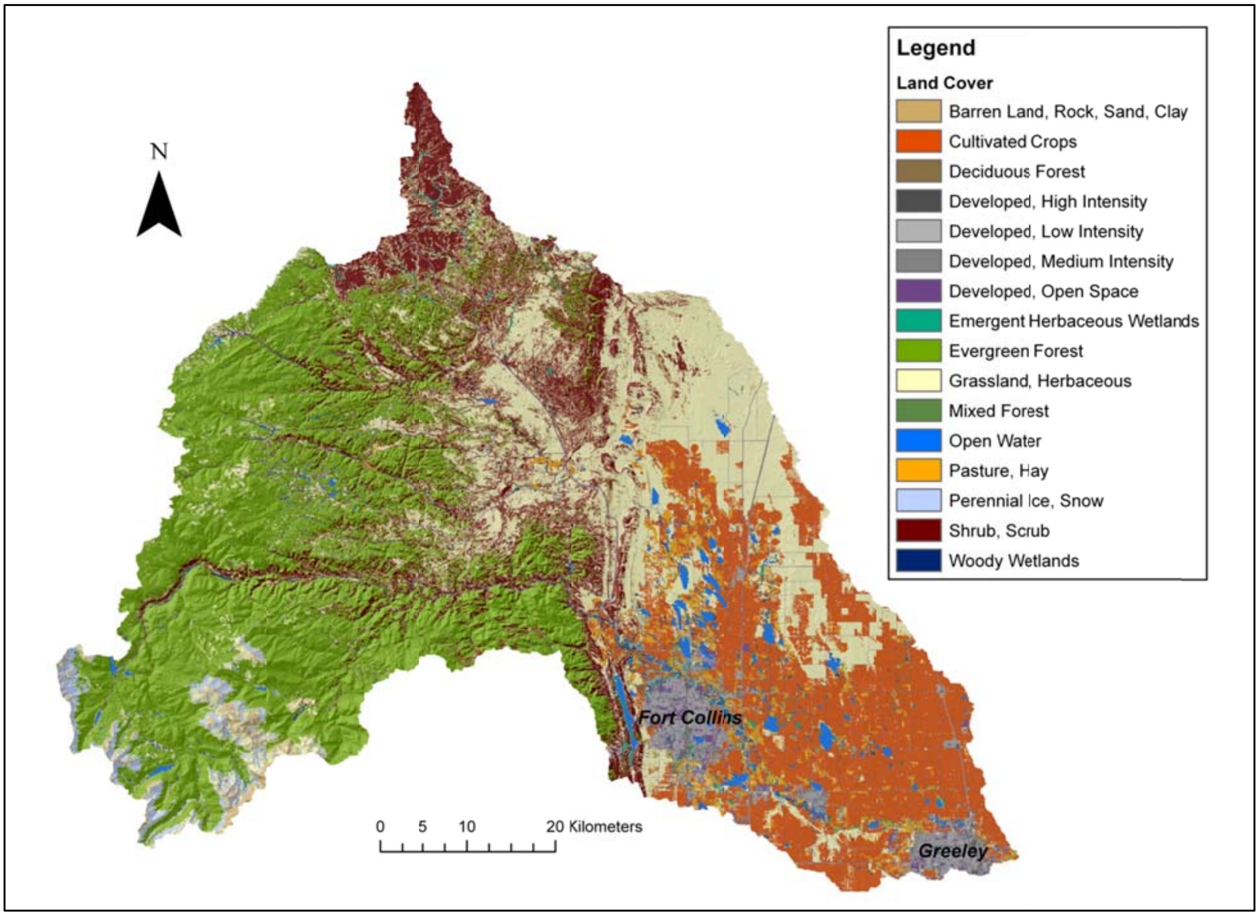

FIGURE 3. Land cover for the Cache la Poudre basin derived from the 2001 National Land Cover Dataset (NLCD).

Climate in the basin varies with elevation, with temperature generally decreasing with elevation while precipitation increases with elevation (Figure 4). Annual average precipitation ranges from 330 mm (13 in) at low elevations to 1350 mm (53 in) in the basin headwaters. Weather station measurements of precipitation show high local variability, but on average, basin precipitation is highest during the spring months (Figure 5). Average annual temperature ranges from 9°C (48°F) at low elevations to less than -5°C (23°F) at the highest elevations.

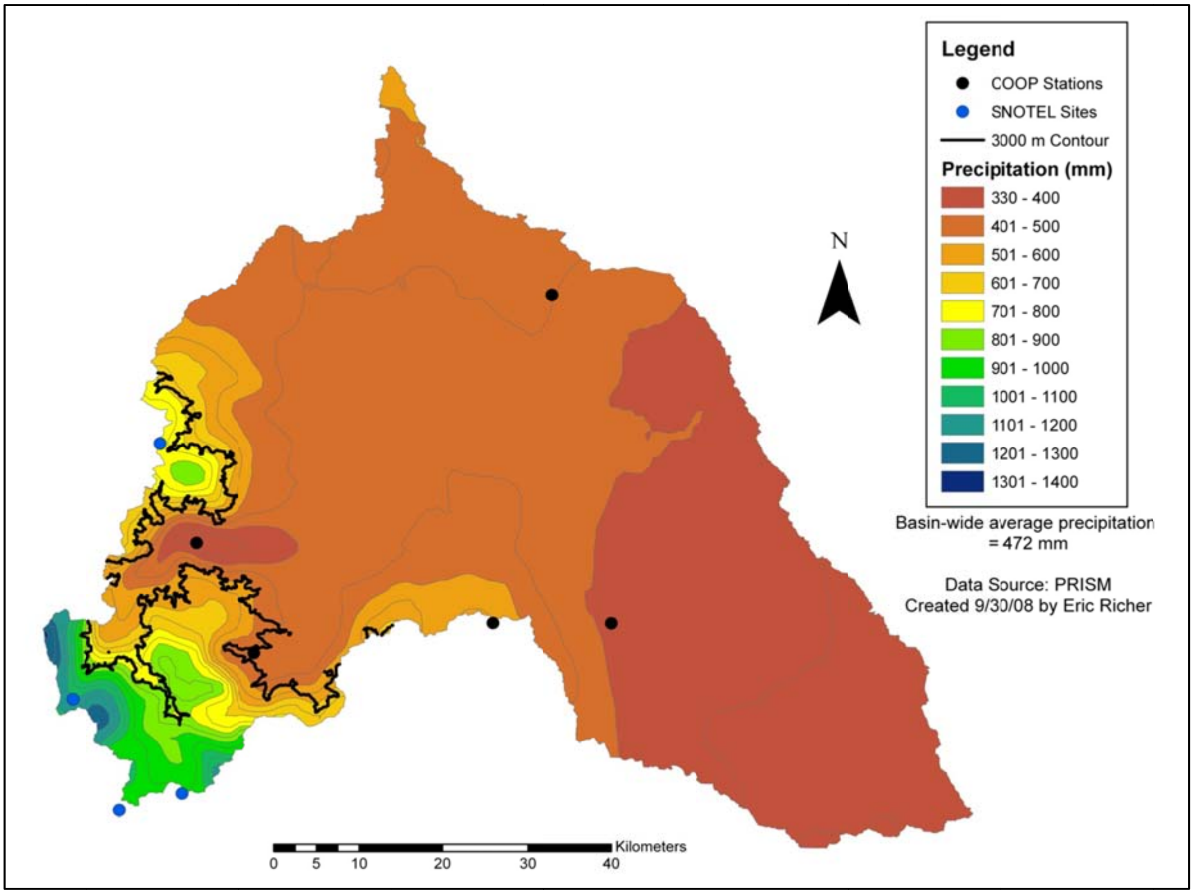

FIGURE 4. Average annual precipitation for the Cache la Poudre basin derived from the PRISM climate model (www.prismclimate.org). Averages calculated over the years 1971-2000.

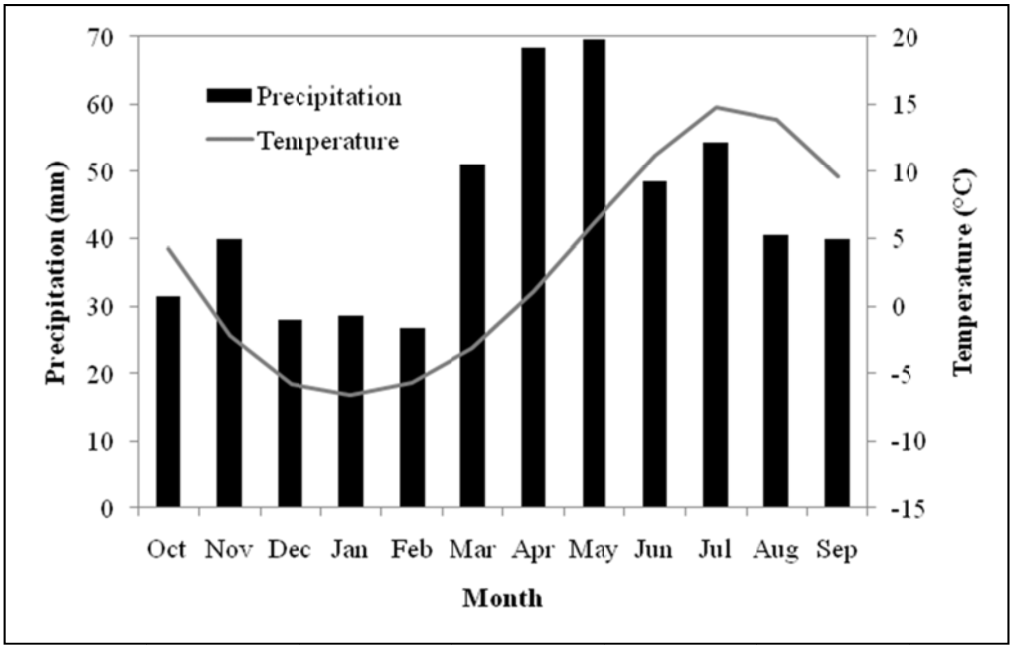

FIGURE 5. Average monthly precipitation and temperature for the Cache la Poudre basin, 1971-2000. Derived from PRISM, Oregon State University, www.prismclimate.org.

Previous research

Predicting river flow in snowmelt-dominated mountain basins can be a challenge, in part because forecasts rely on ground observations of the snowpack that leave much of the land surface area under-sampled in both time and space (Bales et al., 2006). The primary snow variable of interest for river flow prediction is snow water equivalent (SWE), which indicates the amount of water in the snowpack. In the Cache la Poudre basin, SWE measurements are collected continuously at SNOTEL sites and during spring snow surveys at snow course sites (Figure 2). While these sites provide useful information about the snowpack at the measurement locations, local snow measurement sites are not necessarily representative of the snowpack in a larger area (Molotch and Bales, 2005), as SWE can vary significantly over short distances in mountain terrain (Elder et al., 1991; Balk and Elder, 2000).

One strategy for examining a snowpack over a large area is to use remotely sensed images taken from air or satellite. Several methods have been developed to estimate SWE from remotely sensed data (Rees, 2006), but these methods are not well-suited for the steep and varied terrain of mountain basins. Alternatively, studies of mountain basins have derived spatial distributions of SWE using combinations of image data and modeling (e.g. Cline et al., 1998; Molotch and Margulis, 2008) or through data assimilation methods (e.g. NOHRSC, 2004; Kolberg et al., 2006; Andreadis and Lettenmaier, 2006). These types of methods usually incorporate remotely sensed images of the snow-covered area (SCA), a variable much more easily observed from aircraft or satellite images. SCA data have been used in multiple studies for both hydrologic simulation and forecasting (e.g. Tekeli et al., 2005; Dressler et al., 2006; McGuire et al., 2006).

Hydrologic models offer a structure for relating snow variables (SWE or SCA) to runoff generation. These models have a wide range of theoretical frameworks, ranging from simple empirical or conceptual models to more detailed physically based models. Fully empirical models such as multiple regressions or principle components analysis are often employed by flow forecasters to predict seasonal snowmelt runoff from in situ SWE measurements. Fully empirical models do not attempt to represent the physical processes that convert snow to runoff. In contrast, conceptual or physically based models represent the snowmelt runoff process in some way. A widely used snow conceptual model is the snowmelt runoff model (SRM; Martinec et al., 2007), which is designed to simulate snowmelt runoff directly from SCA data. The model links snow cover changes in elevation zones to runoff magnitude using a degree-day melt approach. More detailed physically-based models (e.g. Blöschl et al., 1991; Marks et al., 1999) simulate changes in SWE over space and time based on the snowpack energy balance. Because of the heterogeneity and data scarcity in mountain terrain, these more detailed models are generally best suited for relatively small basins (<10 km^2) although they have been applied with some success over larger areas as well (Garen and Marks, 2005). A reasonable guiding principle for selecting an appropriate hydrologic model for a basin is that the model should contain only as much detail as the data support.

Review of Methods Used

Hydrologic analyses conducted for this project rely on precipitation, temperature, snowpack, and river flow measurements during the snowmelt runoff season, which we define as lasting from March-September. We focused most analyses on the years 2000-2009, as these are the years for which we had both SCA data and daily naturalized flow data.

Data sources

We compiled daily precipitation and temperature data for all COOP meteorological stations and SNOTEL stations within and near the boundaries of the upper Cache la Poudre basin (Figure 2, Table 1). We also compiled maps of annual average precipitation and temperature distributions from the PRISM climate model (Figure 4; www.prismclimate.org). To characterize snowpack properties, we compiled daily snow water equivalent (SWE) values for SNOTEL stations and used snow covered area (SCA) images from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Terra satellite. We used the 8-day maximum SCA product downloaded from the National Snow and Ice Data Center (NSIDC: http://nsidc.org/data/modis/index.html).

TABLE 1. Meteorological and SNOTEL stations within and near the upper Cache la Poudre basin.

Name	**ID**	**Type**	**Elevation (m)**
Fort Collins	53005	COOP	1525
Virginia Dale	58690	COOP	2138
Buckhorn Mountain	51060	COOP	2256
Rustic 57296		COOP	2347
Hourglass 54135		COOP	2902
Joe Wright	05J37S	SNOTEL	3085
Deadman Hill	05J06S	SNOTEL	3115

To analyze how precipitation, snowpack, and temperature relate to river flow, we require ‘naturalized’ flow values. When the Cache la Poudre River reaches the Canyon Mouth stream gauge, its flow has been modified by diversions into and out of the basin and by reservoir storage. Our analyses use naturalized flow values at the Canyon Mouth location calculated using a basic accounting method:

$$\textit{Naturalized flow} = \textit{Observed flow} + \textit{Diversions} - \textit{Foreign water} \pm \Delta \textit{Storage}$$

where *Diversions* are any structures that remove water from the river or its upstream tributaries, *Foreign water* is any water that is imported from outside the basin boundaries into the Cache la Poudre or its upstream tributaries, and Δ*Storage* is any change in the quantity of water stored in reservoirs within the basin. This accounting method does not incorporate routing of flow within the stream network, which contributes some uncertainty to daily naturalized flow values. Calculations of naturalized flow also exclude some smaller diversions that are not monitored continuously. Figure 6 presents an example of naturalized flow relative to observed flow. More details on naturalized flow calculations are available in Richer (2009).

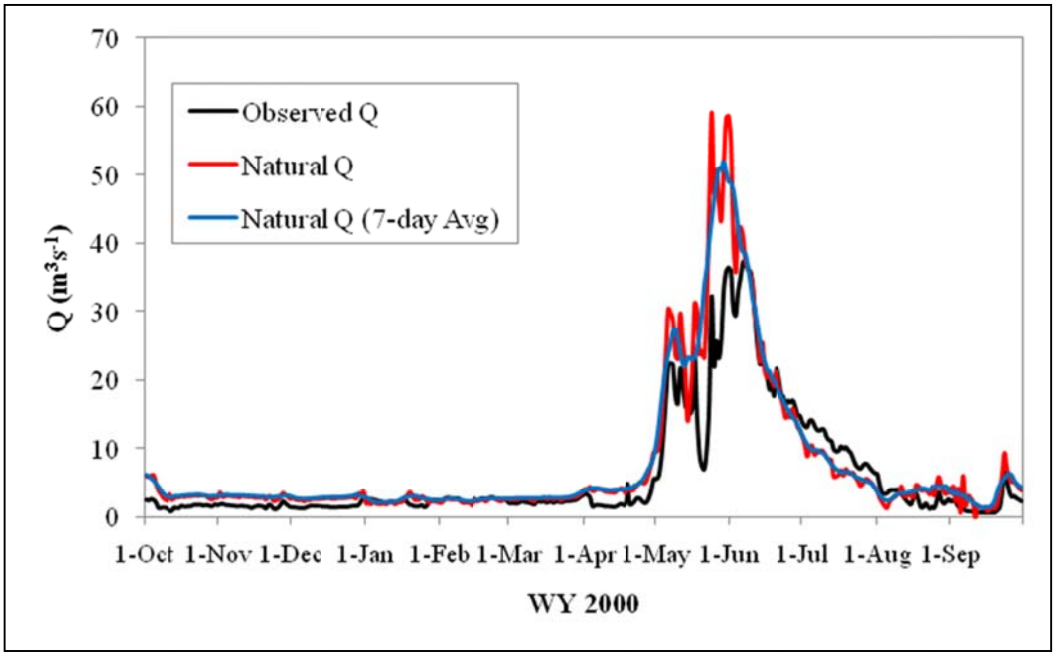

FIGURE 6. Observed and naturalized discharge (Q) for the Cache la Poudre River at Canyon Mouth, WY 2000.

Hydrologic analysis

The first component of our research involved data analyses in which we investigated relations between snowpack variables and March-September naturalized flow at the Canyon Mouth. The first set of analyses examined correlations between SWE and water yield for the period of record of the SNOTEL stations in the basin (1981-present). These statistical analyses were intended to give a first order understanding of how river flow relates to features of the snowpack. We then added SCA data as an additional snowpack variable. SCA data from MODIS are available from 2000-present. To conduct statistical analyses with the SCA data, we divided the basin into sub-units of either sub-basins or elevation zones (Figure 7). For each of these subunits, we examined correlations between SCA and naturalized flow during each individual snowmelt season. We then conducted a more in-depth analysis of the SCA data to characterize the spatial and temporal features of the snowpack during the melt season. We derived maps of weekly "snow cover probabilities", which show the likelihood that a given part of the basin will have snow on the ground for a particular date during the melt season. More details on methods for analyzing SCA data are given in Richer (2009) and Richer et al. (in review).

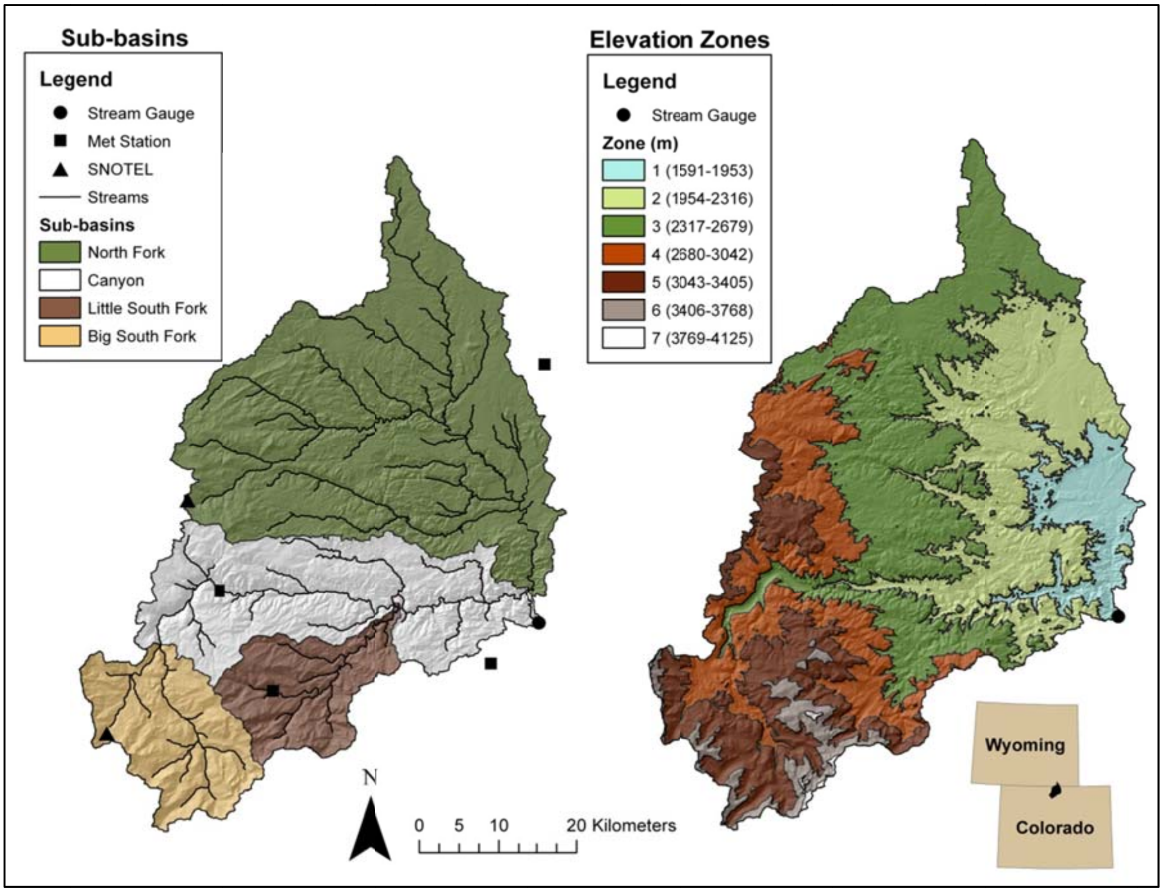

FIGURE 7. Sub-basins and elevation zones used in analyses of SCA; elevation zones are also used in hydrologic simulation models.

Hydrologic modeling

As a complement to the data-based hydrologic analyses, we developed conceptual models that simulate river flow as a function of the climate variables we analyzed: temperature, precipitation, SWE, and SCA. Because the basin has a relatively limited amount of data to inform a detailed hydrologic model, we used a low-parameter conceptual modeling approach that is similar to the structure of the Snowmelt Runoff Model (SRM; Martinec et al., 2007). The SRM model simulates river flow as a function of changes in SCA in elevation zones. Initially, we applied the original version of SRM model to simulate flow for the snowmelt runoff seasons of 2000-2006 using the elevation zones shown in Figure 7. For each year, we ran the model with both calibrated parameters and with standardized parameters, as described in Richer (2009).

We then developed a new model structure that simulates river flow as a function of changes in SWE, rather than changes in SCA as in the original SRM model. We conducted a comparative study of the SCA-driven and SWE-driven model structures to determine which is best suited for simulating the observed river flow in the basin. These methods are reported in greater detail in Kampf and Richer (in preparation). Using the SWE model, we then explore the effects of unknown spring precipitation and temperature on river flow prediction. We create ensembles of possible river flows by varying the time series of spring temperature and precipitation over the basin, starting either on April 1 or on May 1.

Discussion of Results and their Significance

Hydrologic analysis

In the first set of hydrologic analyses, we examined the relations between SNOTEL station measurements of SWE and river discharge. First, we compared naturalized discharge at the Canyon Mouth gauge to SWE measured at the two SNOTEL sites in the basin, Joe Wright and Deadman Hill. These SNOTEL stations are both located close to the basin boundaries (Figure 7). Figure 8 shows the variability of peak SWE at each SNOTEL site relative to the variability of discharge during the snowmelt season, which we define as lasting from March-September. For all years, values of peak SWE stay within 50% of the 1981-2009 mean SWE. River flow (Q) is more variable than SWE. During the highest flow year, 1983, the discharge was over 260% of normal, and during the lowest flow year, 2002, the discharge was only 30% of normal. During 2000-2007, the years when flow forecasts tended to over-predict water yield (Figure 1), river flow was relatively low, having values that were on average 73% of the 1981-2009 mean. SWE during these years was also lower than normal, on average 85% of the 1981-2009 mean.

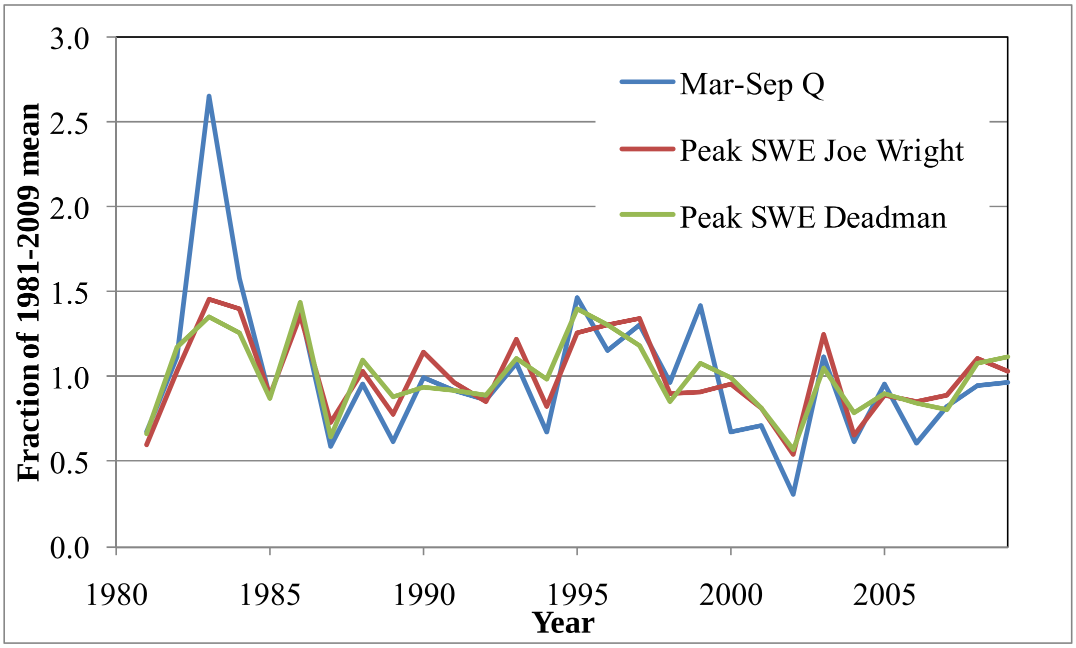

FIGURE 8. Variability in SWE and naturalized March-September discharge (Q) at the Canyon Mouth gauge.

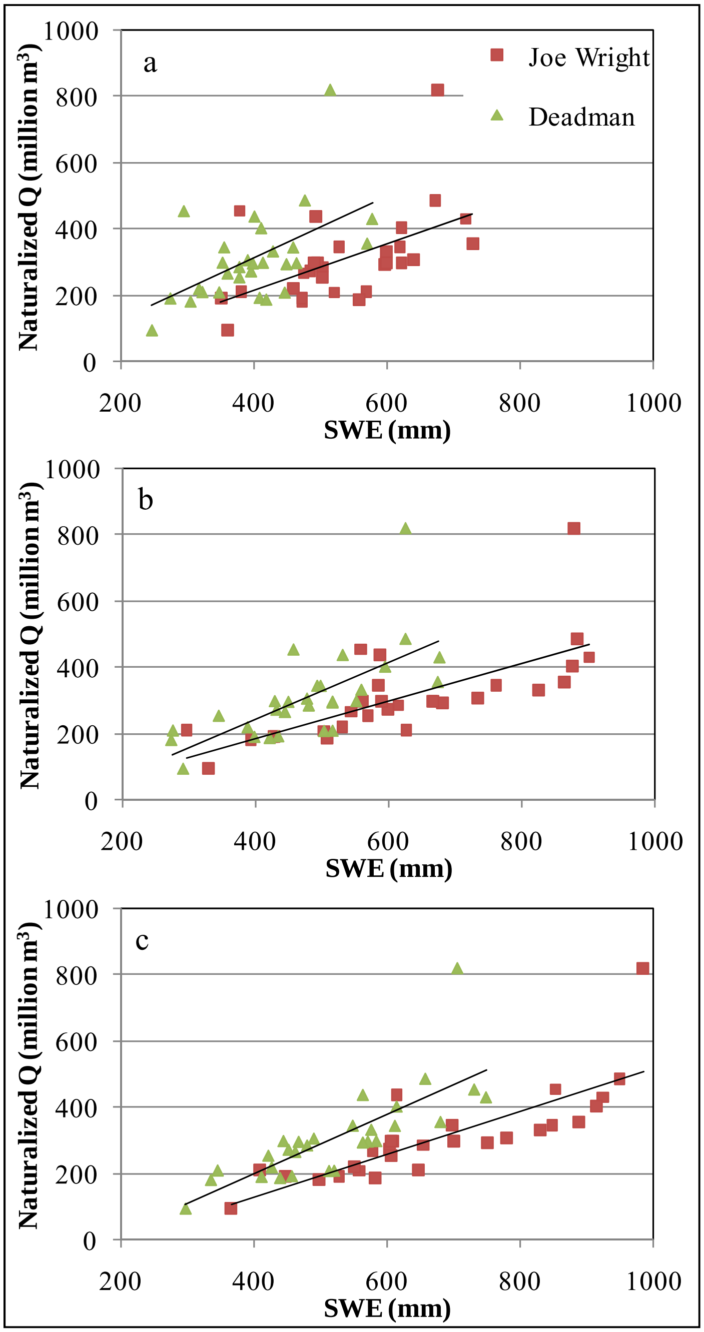

FIGURE 9. March-September naturalized discharge (water yield) at the Canyon Mouth gauge vs. (a) April 1 SWE, (b) May 1 SWE, and (c) Peak SWE.

Even though water yield has higher inter-annual variability than does SWE, the correlation between SWE and naturalized March-September flow is relatively high for peak SWE at both SNOTEL stations (Figure 9; Table 2). While values of SWE are lower at Deadman Hill than at Joe Wright, relations between SWE and discharge are relatively similar for the two stations. Correlations between SWE and water yield are poor on April 1, in part because snow accumulation continues later into the spring at these SNOTEL sites. The average date of peak

SWE is May 2 at Joe Wright and May 4 at Deadman Hill. As a result, correlations between SWE and water yield improve substantially for May 1. However, the date of peak SWE at the two stations can vary from mid-March to early June, meaning that May 1 is not always an ideal date for water yield prediction. The SWE variable that has the highest correlation to March-September discharge is the peak SWE, which explains >60% of variance in discharge. If the outlying high flow year (1983) is excluded, the peak SWE explains >70% of variance in discharge (Table 2).

TABLE 2. Coefficient of determination (R^2) between SWE at SNOTEL stations and naturalized March-Sept discharge at the Canyon Mouth Gauge.

	Joe Wright	**Deadman**
Apr 1, all data	0.29	0.30
Apr 1, excluding 1983	0.28	0.27
May 1, all data	0.50	0.46
May 1, excluding 1983	0.57	0.53
Peak, all data	0.64	0.61
Peak, excluding 1983	0.72	0.73

The two SNOTEL stations are both located at the margins of the basin, Joe Wright at 3085 m elevation and Deadman at 3115 m elevation. An additional SNOTEL station was added at the Hourglass site (2902 m elevation) in 2008, but before then, there were no continuous measurements of SWE at lower elevations within the basin. The MODIS SCA data allow us to examine snow behavior in parts of the basin where in situ measurements are unavailable. Figure 10 shows examples of how SWE at Joe Wright and SCA for the basin as a whole compare to naturalized discharge during snowmelt. During many of the years shown, SWE at Joe Wright continued to accumulate until May. In contrast, SCA for the basin as a whole began to decrease in mid-March each year, well before the high elevation snowpack at Joe Wright had begun to melt. Discharge in the river generally stayed at baseflow levels until mid-April, when it began to rise gradually. River flow rose to peak flow levels in mid-May to early June, when the high elevation snowpack was melting.

To determine whether SCA data provide any useful information for predicting water yield, we examined correlations between SCA and naturalized discharge for spatial subsets of the basin (Figure 7) for years 2000-2006. For these analyses, high R^2 values represent negative correlations between SCA and discharge, implying that the decrease in SCA for middle elevations correlates with rising discharge. These analyses show that correlations between SCA and discharge vary from $R^2 = 0.5\text{-}0.8$ for the basin as a whole (Figure 11). The correlation strength stratifies by elevation (Figure 12), with the highest correlations between SCA and discharge found for a middle elevation zone (2680-3042 m), where the R^2 values are between 0.6-0.9. Correlations between SCA and discharge are relatively weak above and below this middle elevation zone. Additional details about these analyses are given in Richer (2009) and Richer et al. (in review).

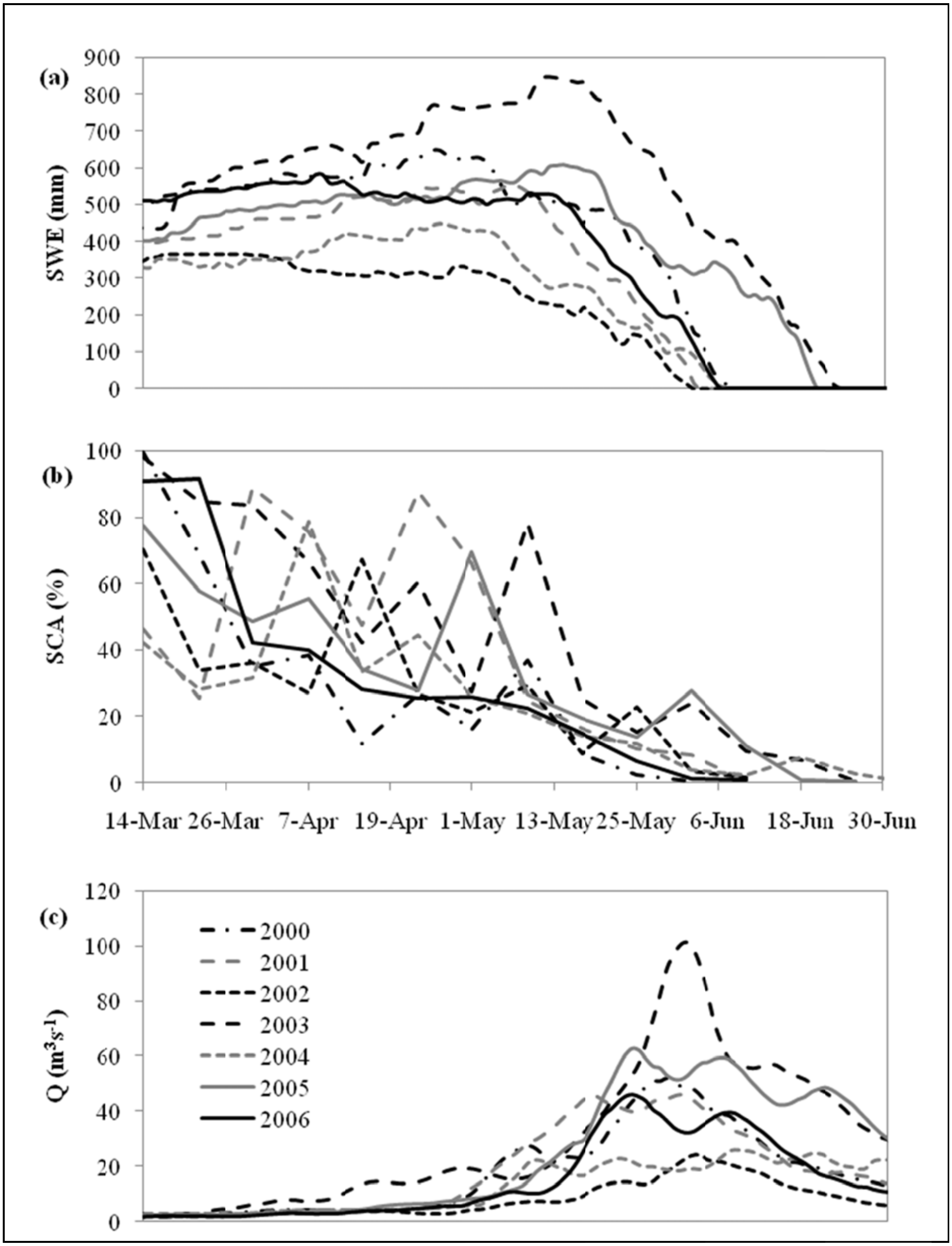

FIGURE 10. Variability in (a) SWE at Joe Wright SNOTEL station (elevation 3085 m), (b) %SCA for the basin derived from MODIS, and (c) 7-day mean naturalized discharge at the Canyon Mouth gauge for 2000-2006.

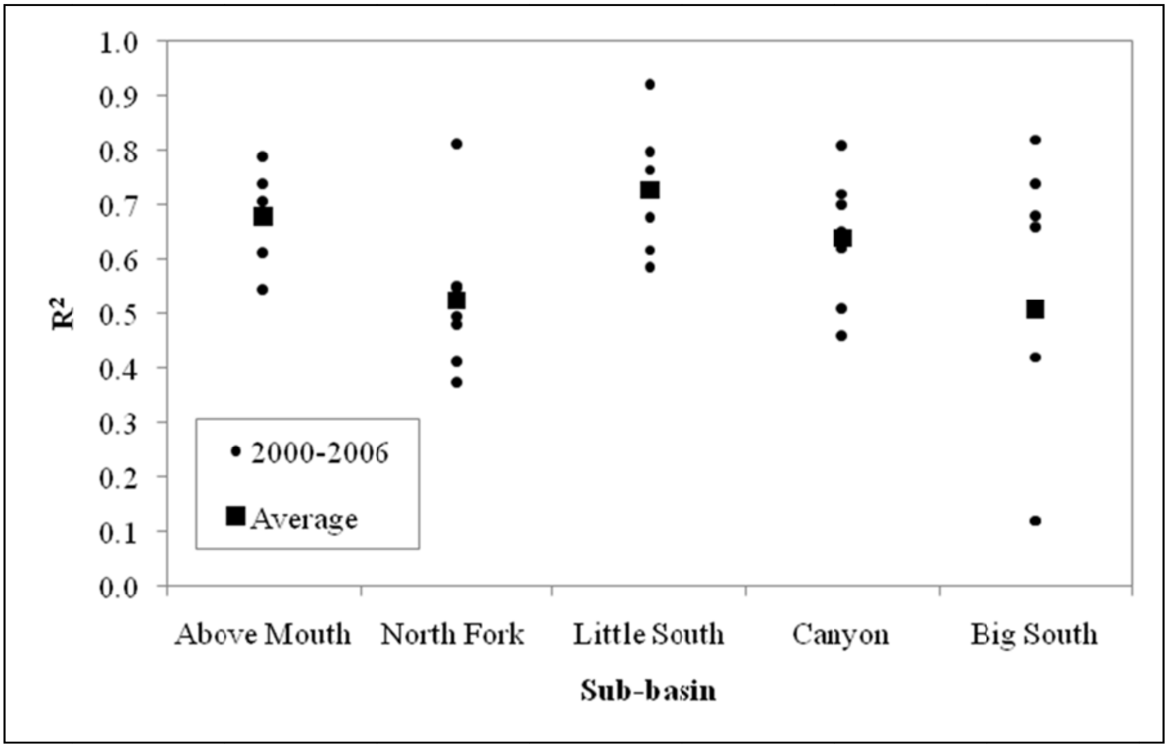

FIGURE 11. Correlation strength (R^2) of the SCA vs. Q relationship during the snowmelt seasons for the entire upper Cache la Poudre basin and for sub-basins, 2000-2006.

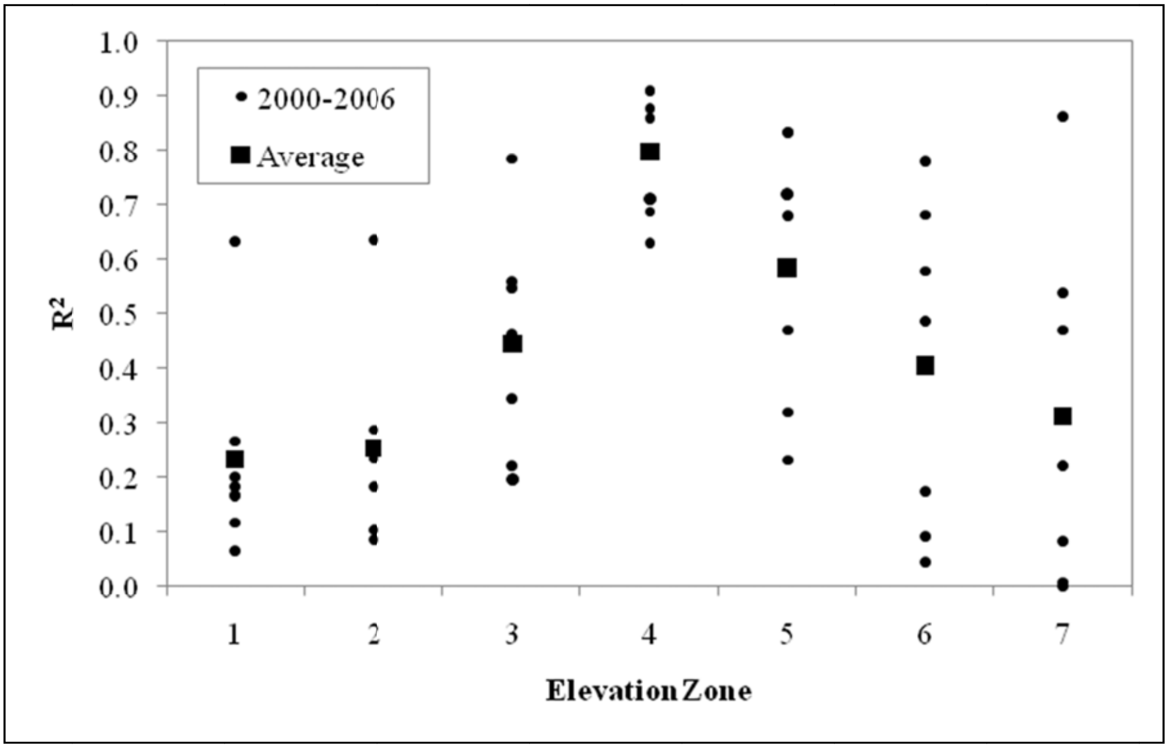

FIGURE 12. Correlation strength (R^2) of the SCA vs. Q relationship during the snowmelt seasons for elevation zones above the Canyon Mouth gauge, 2000-2006.

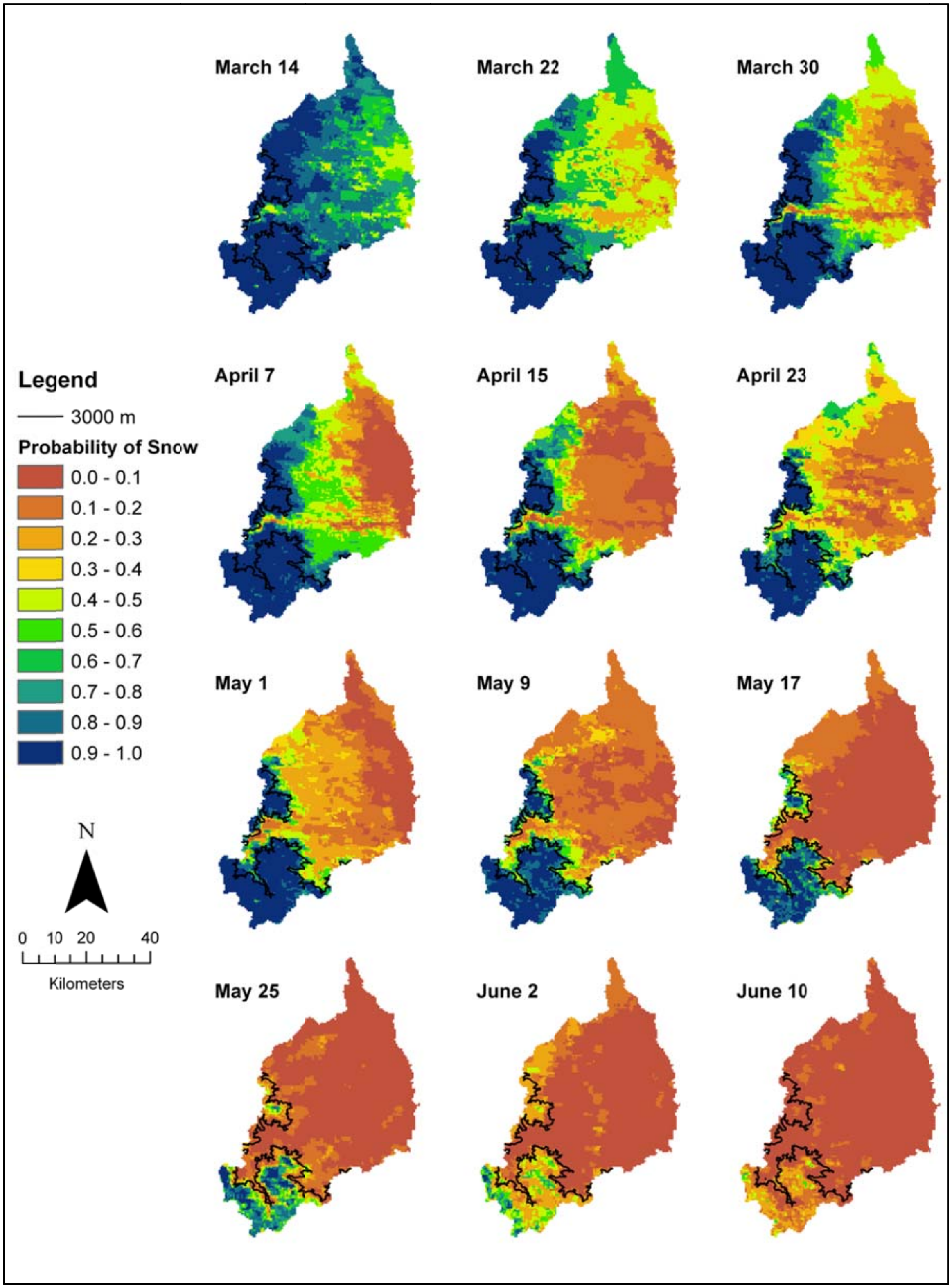

FIGURE 13. Probability of snow time series for the upper Cache la Poudre basin derived from MODIS 8-day snow covered area images. For each date, probabilities are calculated using images from 2000-2006.

To explore the spatial patterns of SCA in greater detail, we developed composite images that demonstrate the likelihood of snow cover for each pixel in the basin during the snowmelt season (Figure 13). As shown in Figure 13, the "Probability of Snow" for each pixel is calculated as the number of images with snow cover on the specified date divided by the total number of images in the period of analysis. Values of 1 indicate that all images on the specified date were snow-covered; values of 0 indicate that no images on the specified date were snow-covered. The probability of snow cover for the basin shows a gradual change with elevation during late March and early April. By mid-late April, however, the probability of snow images develop a sharp transition between low snow cover and high snow cover. This sharp transition zone develops just below approximately 3000 m elevation, in the range of the middle elevation zone (4) highlighted in Figure 12. The snow cover is intermittent below this transition zone, whereas snow cover persists well into the spring above the transition zone.

Our snow cover analyses showed that the snowed cover transition zone is a prominent feature of the basin snowpack. Snow cover changes only correlated consistently with runoff timing within this mid-elevation transition zone (Figure 12), which is located below the elevations of SNOTEL measurements of SWE. Information about the spatial extent of the seasonal snowpack in these lower elevations could potentially be helpful in predicting early season runoff. Our initial analyses comparing SCA in the transitional elevation zone to river flow during 2000-2006 suggested that SCA in early April could be a strong predictor of March-September water yield. However, subsequent analyses including additional years of data showed mixed results. Figure 14 and Table 3 compare predictions of March-September discharge using either April 1 SWE or SCA from March 29 or April 6 in the snow transition zone (4). The SCA dates correspond to the dates when 8-day maximum SCA images from MODIS were available. Of the variables tested in Figure 14, SCA on April 6 had the strongest correlation to water yield, but its R^2 value was still only 0.59.

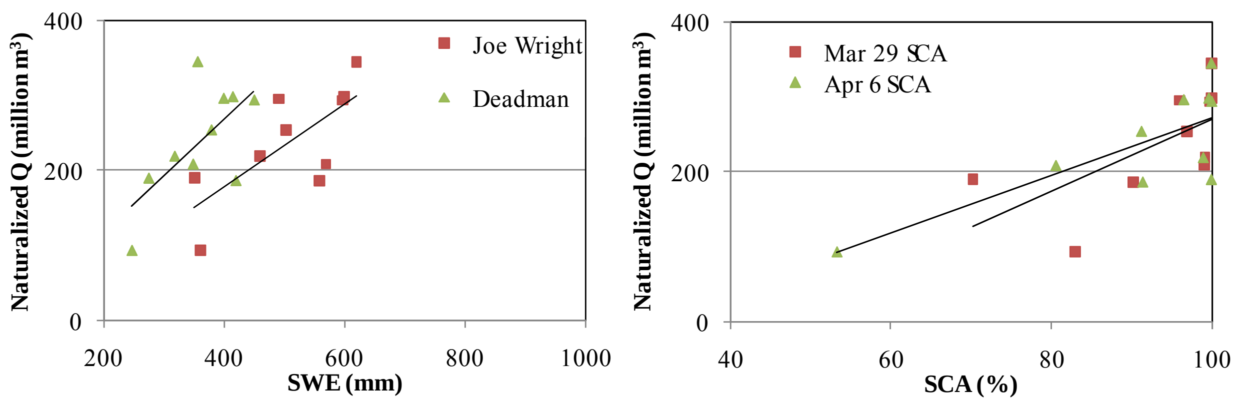

FIGURE 14. Naturalized March-September discharge at Canyon Mouth vs. April 1 SWE (left) and zone 4 SCA (right) during 2000-2009.

TABLE 3. Coefficient of determination (R^2) between snow variables (SWE at SNOTEL stations or SCA in elevation zone 4) and naturalized March-Sept discharge at the Canyon Mouth Gauge. R^2 values are derived from measurements during 2000-2009.

	R^2
Apr 1 SWE, Joe Wright	0.53
Apr 1 SWE, Deadman	0.44
Mar 29 SCA, zone 4	0.41
Apr 6 SCA, zone 4	0.59

After the first week of April, SWE always out-performed SCA as a predictor variable for water yield. In part this is because SCA only has potential benefit as a runoff predictor variable in areas like the snow transition zone, where snow cover depletion correlates with a river flow response. SCA has limited utility in representing runoff under conditions when snow is melting from an area that remains entirely snow covered. During 2007-2009, for example, SCA in the transitional elevation zone was at or near 100% on March 29 and April 6 (Figure 14), making it impossible to use SCA to distinguish between flow volumes for these years. Additional years of data are likely needed to determine whether and how SCA data can be a useful quantitative addition to statistical flow forecasts. Qualitatively, however, the SCA data do demonstrate how rapidly snow cover depletes from the basin and where the snowpack is seasonally persistent. Both of these types of information are useful for determining how much of the basin area is likely to contribute to river water yield.

Hydrologic modeling

Hydrologic simulation models enable us to explore mechanistic relationships between the snow variables we analyzed (SWE and SCA) and river flow. We developed two separate simulation models, one driven by changes in SWE and the other driven by changes in SCA. These models simulate discharge at the Canyon Mouth gauging location at a daily time step during March-September for 2000-2009, the years when SCA data were available for the basin. Models both have strong performance (Table 4), with average Nash-Sutcliffe Efficiency Coefficients (NSCE) of 0.90 for the SCA model and 0.91 for the SWE model. Mass balance performance is described by the Bias statistic (B), which indicates the fractional difference between measured and simulated total March-September discharge. The SWE model has a low mass balance error on average, whereas the SCA model tends to under-predict total discharge. Additional details on hydrologic model calibration and performance are given in Kampf and Richer (in preparation).

TABLE 4. Performance statistics for SCA-based and SWE-based snowmelt runoff models. Values are calculated using observed naturalized discharge compared to simulated discharge for the Canyon Mouth gauge for each March-September simulation period.

Year	**SCA model**		**SWE model**	
	NSCE	*B*	*NSCE*	*B*
2000	0.96	-0.04	0.93	0.00
2001	0.94	-0.05	0.95	0.00
2002	0.94	0.04	0.85	0.00
2003	0.71	-0.14	0.92	-0.02
2004	0.81	-0.06	0.83	0.00
2005	0.94	-0.07	0.95	0.02
2006	0.93	-0.06	0.91	-0.01
2007	0.93	-0.01	0.94	-0.01
2008	0.92	0.00	0.89	0.04
2009	0.94	-0.10	0.90	0.00
MEAN	*0.90*	*-0.05*	*0.91*	*0.00*

Figure 15 shows examples of model performance during the years 2002, a low flow year, and 2003, a relatively high flow year. During the low flow year, 2002, the SCA model over-predicted the total flow volume, whereas during the high flow year, 2003, the SCA model significantly under-predicted the total flow volume. The SWE model had more consistent mass balance performance from year to year. Both simulation models were configured to represent runoff generation from elevation zones, so they can demonstrate which parts of the basin were likely to be contributing the most water to the river. The average contributions to runoff by elevation zone are shown in Figure 16. The SWE model shows that >50% of the river flow on average came from elevation zone 5, which is just above the transitional elevation zone (4) that we identified previously from snow cover analyses (see Figures 7 and 12). The SCA model also showed the highest fraction of river discharge coming from zone 5.

The parts of the basin that cover the largest total surface area (zones 2 and 3) contribute only a minor fraction of total river flow in the SWE model. The SCA model shows a slightly larger contribution to river flow from these low elevation zones; this difference between models relates to the model structure. The SCA model can only simulate changes in river flow when there is a change in the snow-covered area. In contrast, the SWE model can simulate changes in river flow when SWE depletes, but SCA stays constant. Our data analyses indicate that the SWE model is likely a more accurate representation of the spatial distribution of runoff generation. In that model, the snow transition zone (4, elevations 2680-3042 m), had a variable contribution to total basin water yield each year. In 2003, the highest flow year during the 2000-2009 study period, zone 4 contributed 33% of the basin water yield. At the other extreme, in 2006, a low flow year in which flow forecasts overestimated water yield (Figure 1), zone 4 contributed only 2% of the total water yield in the SWE model.

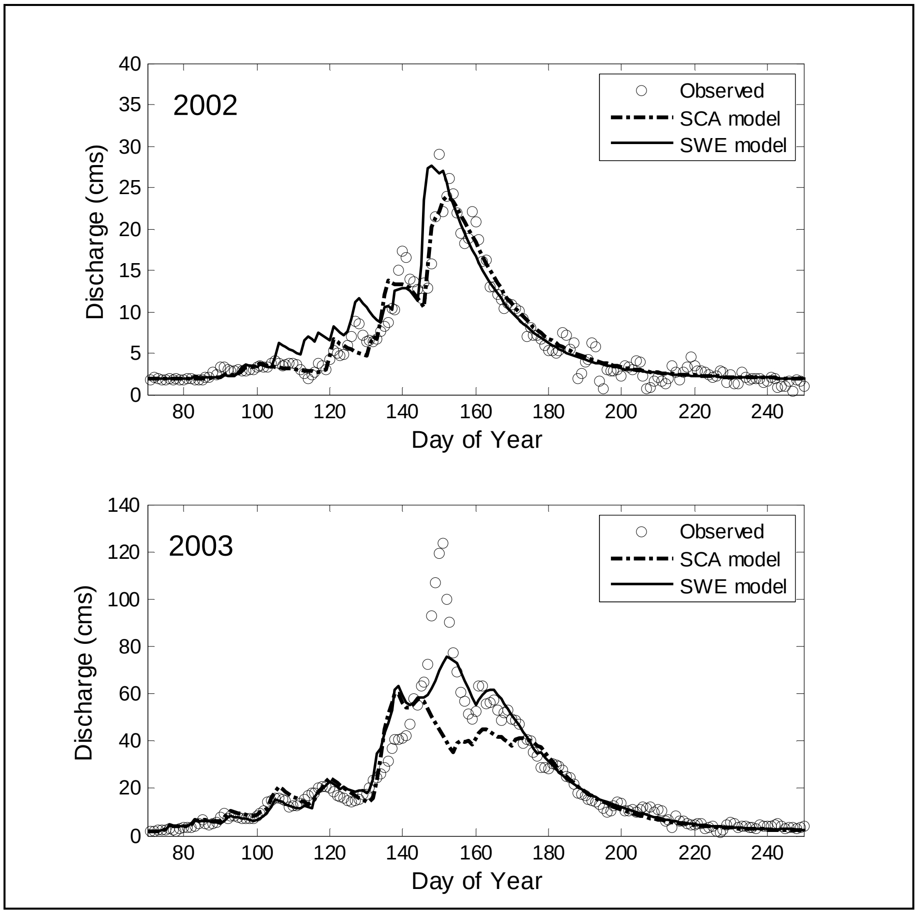

FIGURE 15. Observed naturalized discharge and simulated discharge at the Cache la Poudre Canyon Mouth gauge for 2002 and 2003.

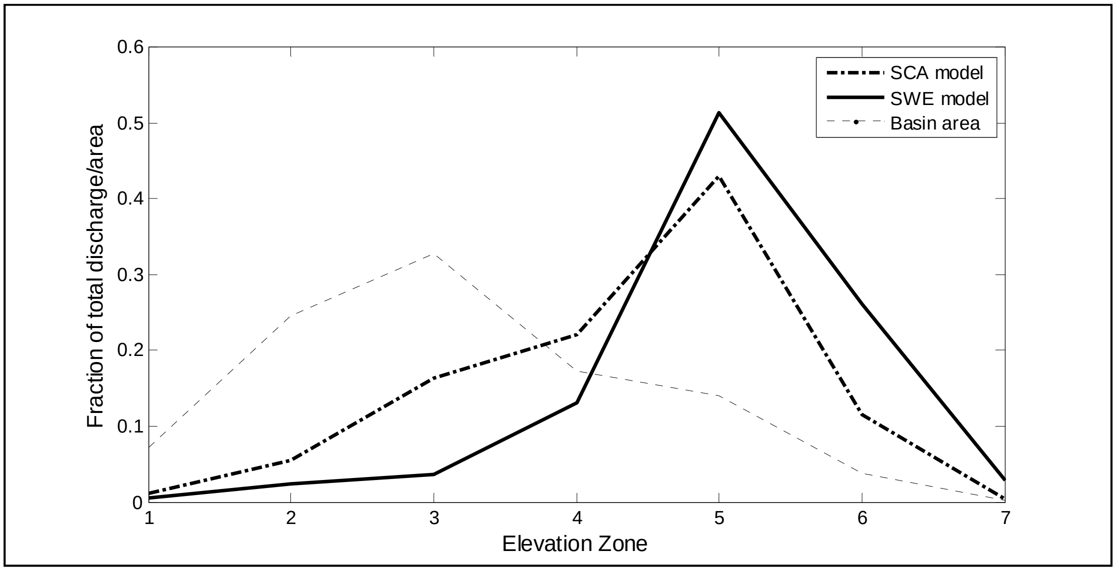

FIGURE 16. Average runoff production by elevation zone for the SCA model and SWE model during 2000-2009. For reference, the plot also shows the fraction of total basin area within each elevation zone.

After developing and testing the SWE model, we used this model to examine the sensitivity of river flow to spring precipitation and temperature. Because this basin receives high spring precipitation (Figure 5) and often does not experience peak SWE until after May 1, the behavior of the weather in the spring months could have a significant effect on the ability to forecast seasonal river flow. Here we illustrate an example sensitivity analysis for the year 2001. In this example, we assume that the SWE on March 1 is represented by an average lapse function that assigns low SWE to low elevation and higher SWE to high elevations. Each simulation run proceeds at a daily time step starting with this same March 1 SWE distribution and the input precipitation and temperature values from 2001 climate data. Test scenarios then assume (1) temperature is unknown for April 1 to September 30, (2) precipitation is unknown for April 1 to September 30, (3) temperature is unknown for May 1 to September 30, and (4) precipitation is unknown for May 1 to September 30. Each test scenario is run ten times, with the ten ensemble runs taken from the observed temperature or precipitation record for 2000-2009.

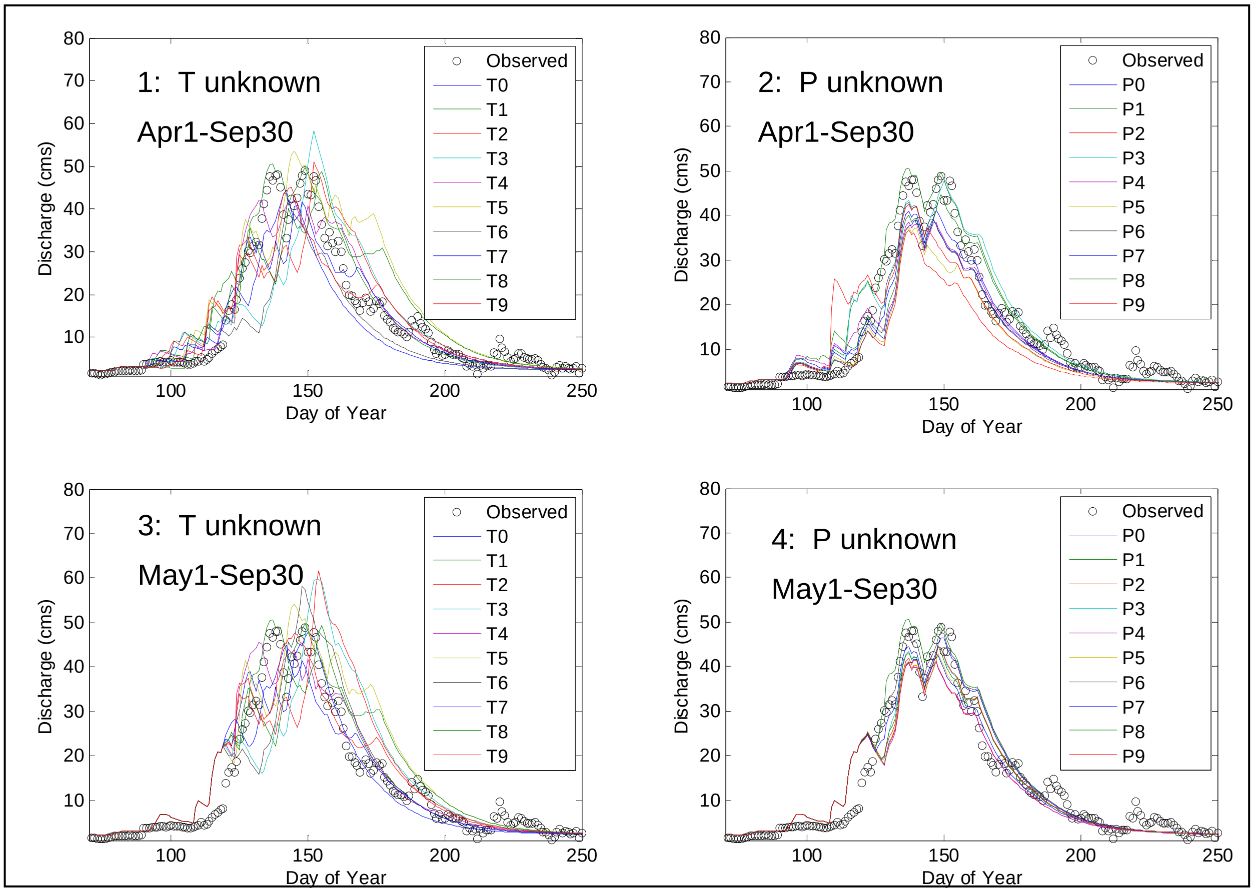

FIGURE 17. SWE model ensemble simulations illustrating the sensitivity of 2001 discharge to spring precipitation and temperature. (1) Temperature varies in each simulation run starting on April 1; (2) Precipitation varies in each simulation starting on April 1; (3) Temperature varies in each simulation starting on May 1; (4) Precipitation varies in each simulation starting on May 1. For each set of scenarios, varying time series of temperature and precipitation are taken from observed records for 2000 (T0, P0) to 2009 (T9, P9).

Figure 17 illustrates the results of these ensemble simulation tests. The first two scenarios are intended to represent river flow prediction starting on April 1. Scenario 1 assumes that precipitation is known, but temperature is unknown from April 1 – September 30. Varying the temperature in each of the ensemble runs creates a wide range of simulated hydrographs, which lead to total simulated flow volumes that range from 26% higher than observations to 24% lower than observed flow (Figure 18). Where the precipitation is unknown, but temperature is known (Scenario 2), the range of simulated hydrographs is slightly smaller, from 11% higher than observed flow to 31% lower than observations (Figure 18). Scenarios 1 and 2 demonstrate that without prior knowledge of precipitation and temperature for the melt season, it is difficult to predict accurate hydrographs. Ensemble scenarios are less variable where precipitation and temperature are unknown starting later in the spring (May 1 in Scenarios 3 and 4). For the May 1 scenarios, variable temperature creates a wider range of simulated hydrographs than variable precipitation (Figures 17, 18).

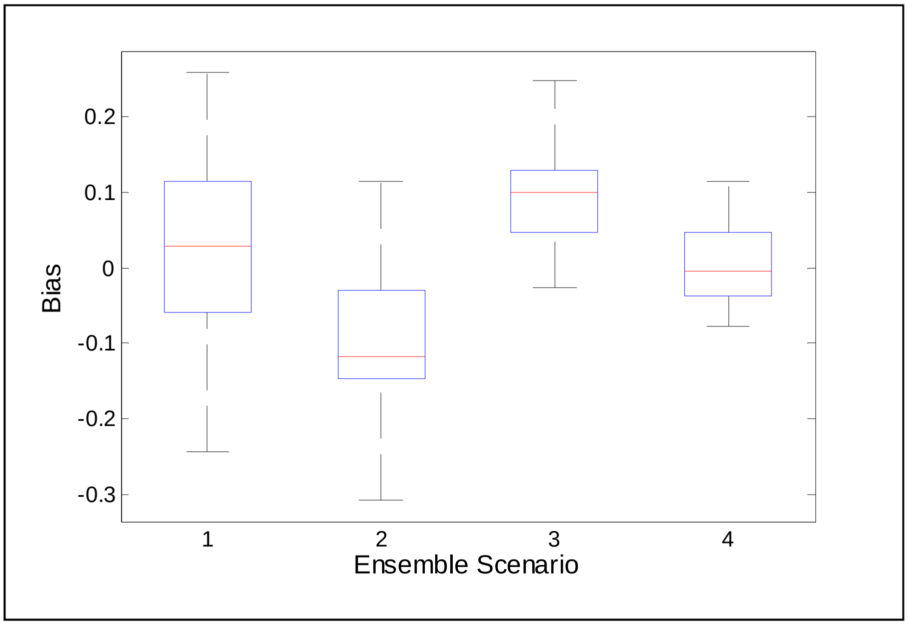

FIGURE 18. Box and whisker plot of the bias distribution for each set of hydrograph ensembles in Figure 17. The bias is calculated as the fractional difference between the total flow volume of the simulation and the total flow volume observed in 2001.

These model sensitivity tests highlight the importance of spring temperature in determining the magnitude and timing of river flow. In the model, temperature during the spring controls both the melting of the snowpack and whether spring precipitation falls as rain or as snow in different elevation zones. Temperature patterns that favor snow accumulation can end up resulting in more simulated runoff because runoff coefficients are higher in the model for snowmelt than they are for rainfall. Sensitivity to temperature in the simulations is also a result of the model structure for simulating the fraction of melt water that reaches the river. Early in the spring, the model assumes that most of the melt water infiltrates and is not available for runoff, whereas later in the melt season, the ground becomes saturated, and more of the melt water reaches the river. Additional research could explore alternate model structures to examine whether different models predict similar sensitivities to spring temperature and precipitation.

Principle Findings, Conclusions, and Recommendations

Hydrologic analyses and modeling results from this study highlight several key features of the snowpack and runoff production in the upper Cache la Poudre basin:

1. Snow cover analyses show seasonally persistent snowpack above around 3,000 m (9,800 ft) elevation that lasts through the winter and early spring.. The snow cover is intermittent below around 2,700 m (8,900 ft) elevation.

2. Modeling results indicate that on average 50% of the total basin water yield comes from the elevation zone between about 3,000-3,400 m (SWE model, Figure 16).

3. The transitional elevation zone identified from snow cover analyses (2,700-3,000 m) has a variable contribution to runoff; in the highest flow year of our study period, 2003, model results indicated that this zone produced 33% of the total water yield, whereas in a lower flow year, 2006, this zone produced only 2% of the total water yield.

4. The timing of snow cover depletion in the transitional elevation zone correlates with the timing of the rising hydrograph, but peak runoff typically does not occur until the higher elevation snowpack begins to melt.

Our results also demonstrate several challenges in spring predictions of water yield in the Cache la Poudre:

1. April and May are the months with the highest average precipitation in the basin (Figure 5). Forecasting is difficult without a priori knowledge of the spring precipitation.

2. Peak snow water equivalent at the two high elevation sites has occurred as early as March 18 (2002 at Joe Wright) and as late as June 2 (1995 at Joe Wright). This variability in the timing of spring snow accumulation means that it is difficult to predict water yield on fixed dates. While peak snow water equivalent explains >60% of variance in water yield from 1981-2009, April 1 SWE and May 1 SWE predict only 30 and 50% of variance in water yield, respectively (Table 2).

3. March-September water yield in the Cache la Poudre River at the Canyon Mouth has greater variability than peak snow water equivalent at the two high elevation SNOTEL sites, Deadman Hill and Joe Wright (Figure 8). Our modeling results suggest two possible causes for variability in water yield that is inconsistent with variability in peak SWE:

    a. The elevation zone with transitional snowpack (2700-3000 m) contributes a variable fraction of total water yield, meaning that in some years a high quantity of runoff is produced in this zone, whereas in other years the runoff production in this zone is low. Additional measurements of SWE in these transitional elevations, for example the new SNOTEL site installed at Hourglass, should be helpful for water yield prediction.

b. The timing of spring warming may also affect the quantity of snow that becomes runoff. Model sensitivity tests show that even when spring precipitation is known, differences in spring temperature patterns can produce differences in water yield (Figures 17, 18).

Because we only examined existing measurements of hydrologic variables in this study, our results do not demonstrate the importance of other factors such as dust on snow, sublimation, soil moisture, or groundwater recharge on river discharge. Given the variables we analyzed, we conclude that the challenges in forecasting water yield in the Cache la Poudre relate primarily to (1) high variability in spring precipitation and temperature patterns, which cause the timing of peak snow accumulation to vary from mid-March to early June, and (2) high variability in the quantity of runoff production from the transitional 2,700-3,000 m (8,900-9,800 ft) elevation zone. Future work could incorporate additional hydrologic processes into simulation models and test the sensitivity of water yield to other factors not tested in this study.

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