THESIS

USING SNOW TELEMETRY (SNOTEL) DATA TO MODEL STREAMFLOW:

A CASE STUDY OF THREE SMALL WATERSHEDS IN COLORADO AND WYOMING

Submitted by

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ABSTRACT

USING SNOW TELEMETRY (SNOTEL) DATA TO MODEL STREAMFLOW:
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The use of operational snow measurements in the Western United States is instrumental in the successful forecasting of water supply outlooks. The focus of this study is to determine if hydro-meteorological variables available from Snow Telemetry (SNOTEL) stations could successfully estimate the annual total runoff (Q_{100}) and components of the hydrograph, in particular, the date of the passage of 20% of the Q_{100} (tQ_{20}), 50% of Q_{100} (tQ_{50}), 80% of Q_{100} (tQ_{80}), and the peak runoff (Q_{peak}). The objectives are to: (1) determine the correlation between streamflow and hydro-meteorological variables (from SNOTEL station data); (2) create a multivariate model to estimate streamflow runoff, peak streamflow, and the timing of three hydrograph components; (3) run calibration/testing on the model; and (4) test the transferability to two other locations, differing in catchment area and location.

Snow water equivalent (SWE) data from the Natural Resources Conservation Service (NRCS) Joe Wright Snow Telemetry (SNOTEL) was correlated to streamflow at the United State Geological Survey (USGS) Joe Wright Creek gauging station. This watershed is located between the Rawah and Never Summer Mountains in Northern Colorado and has a drainage area of 8.8 km^2. Temperature data were not used due to non-stationarity of this time series, while the SWE data were stationary over the 33-year period of record. From the SNOTEL SWE data, peak SWE,

date of peak SWE, and number of consecutive days with snow on the ground up to the date of peak SWE had the strongest correlation to streamflow (R^2 = 0.19 to 0.58).

A collection of models runs were tested with various SNOTEL variables to develop optimal models for each of the five hydrograph components (tQ_{20}, tQ_{50}, tQ_{80}, Q_{100}, Q_{peak}). Five of the six estimates of were made at the date of Peak SWE. A refined estimate was made for the Q_{100} at melt-out, when the SWE equaled zero at the SNOTEL station. For the model development, most of the model trials (78%) had a Nash-Sutcliffe coefficient of efficiency (NSCE) value of greater than 0.50. The variables were analyzed for collinearity through a Variance Inflation Factor (VIF). Models with low collinearity (VIF < 5) and greatest accuracy from the calibration and testing periods were selected as optimal model configurations for each of the hydrograph components. The optimal model configuration in the Joe Wright Creek watershed had strong performance for the tQ_{20}, tQ_{50}, Q_{100} and Q_{peak} (NSCE > 0.50). The tQ_{80} model was the least accurate model (NSCE = 0.32).

Applying the optimal model equation to the two larger watersheds; Shell Creek is located in Big Horn Mountains of Northern Wyoming (with a drainage area of 59.8 km^2) and Booth Creek is located north of Vail in Central Colorado (with a drainage area of 16.0 km^2). Basin specific coefficients were generated for a calibration period (1980 to 1996), and evaluated for a testing period (1997 to 2012). A majority of the model outcomes were considered good, with 72% of the outcomes having NSCE > 0.50. The Q_{100} at melt-out model performed the best (NSCE = 0.62 to 0.94).

In a final analysis, the Joe Wright Creek coefficients were applied directly to the two larger watersheds to test model transferability. The location specific model coefficients did not perform well for the other two basins. However, for the Shell Creek watershed, results were still good for the following variables: tQ_{20}, Q_{100} (using data up to peak SWE and using all SWE data including melt-out) and Q_{peak}, with NSCE values of 0.45, 0.46, 0.47, and 0.37, respectively. The similar results between Joe Wright Creek and Shell Creek watersheds suggest comparable physiographic characteristics between the two watersheds. An earlier observed onset of snowmelt (as indicated by tQ_{20}) at the Booth Creek watershed influenced the overall accuracy of the model transferability. Despite the differences in the transferability of the model, the optimal configured models derived from accessible SNOTEL data and basin specific coefficients serve as a beneficial tool to water managers and water users for the forecasting of hydrograph components.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 The Importance of Snow

The influence of the seasonal snowmelt runoff on surface water resources has been well documented (Doesken and Judson 1996, Cooley and Palmer 1997, Serreze et al. 1999, Pagano et al. 2004, Clow 2010). Snowmelt runoff has been estimated to contribute 50% to 80% of the annual runoff in the Western United States (Doesken and Judson 1996, Pagano and Garen 2006, Day 2009). The effective management of this limited natural resource in the Western United States is vital to the livelihood, prosperity and sustainability of the cultural and environmental assets of the region (Pagano et al. 2004). Snowmelt supplied water resources satisfies the demand for agriculture, municipal, hydropower, recreational and environmental uses (Ferguson 1999, Werner 2006, Perkins et al. 2009).

In a high snow accumulation year and/or years with high runoff, flooding streams and rivers can lead to costly damages and threaten the loss of lives (Cooley and Palmer 1997). Years with low snowpacks and the associated low runoff affect water supplies to industries that so heavily rely on water for their economic success, as well as for the downstream environment. Additionally, with the demand for water increasing, the uncertainty in climate change, a higher frequency of droughts, and the spatiotemporal variability of the snowpack have all escalated conflicts among water users (Gleick 1987, Kult et al 2012).

Furthermore, the spatiotemporal variability of snowmelt runoff can greatly impact water users and interests, furthering the importance of reliable snowmelt modeling. Proper planning for such future uncertainty will be fundamental to the quantity, as well as quality, of our water resources.

1.2 Snowmelt Modeling

Successfully modeling the annual (even daily) fluctuations in snowmelt and seasonal water yields relies largely on accurate representation of the melt process (Hock 2009). Snowmelt runoff models vary in complexity and sophistication but work with the general approach of simulating the ablation of the snowpack using variables that directly or indirectly approximate the energy that diminish the snowpack (Ferguson 1999, Hock 2009, Day 2009). As such, energy balance models (direct) and temperature index models (indirect) each have benefits and limitations (Ferguson 1999, Hock 2003 and Day 2009).

While snowmelt modeling predicts the output of water from a melting snowpack, streamflow forecasting typically uses statistical regression of meteorological variables and correlates them to streamflow to predict a volume of runoff over a period of time (Pagano et al. 2004). For example, in the Western United States, snow water equivalent (SWE) from the first of the month measured during the winter (usually January to May) are used to estimate summer runoff volumes (cumulative runoff from April 1st to September 30th). Specific methods and the history of operational water supply forecasting are outlined in Pagano and Garen (2006). Since snowmelt runoff is so interconnected to the populations, communities and industries of a region, the annual streamflow forecasting plays an extremely important role in water planning and management, not only in the Western United States but also worldwide.

The common goal among successful modeling and forecasting of runoff is the use of accurate, representative and complete hydro-meteorological data (Richard and Gratton, 2001). Operational snowpack measurements have been extensively used for water supply outlooks (Pagano et al. 2004). Streamflow volume forecasts were originally derived through simple regression analysis from manual snow course measurements of snow water equivalent (SWE) and streamflow. The manual snow course surveys started in the mid-1930s, and starting in the late 1970s they have been supplemented and replaced with automated Snow Telemetry (SNOTEL) stations; snow courses and SNOTEL stations are usually located in headwater catchments (NRCS, Cooley and Palmer 1997, Serreze 1999). The technology utilized at the more than 700 SNOTEL stations across the Western U.S. are described in Serreze et al. (1999) and NRCS.

1.3 SNOTEL Data

While SNOTEL data have been scrutinized for their limitations (spatial representatively of the basin snowpack) and quality control (missing and erroneous values) concerns, technological advances have improved the quality and benefits of the vital data (Serreze et al. 1999, Leibowitz et al 2012). One such strategic advantage of the automated SNOTEL station is the continuous collection of real-time daily and even hourly data, providing vital information to water managers (Clow 2010). Specifically, these continuous data provide precise measurements of snowpack characteristics at a point, as opposed to the standard manual snow course measurements taken monthly or occasionally semi-monthly. Thus a benefit of the SNOTEL network is that the daily data can capture the actual peak SWE and can be used to define other specific characteristics of the snowpack, such as the number of days of accumulation or melt.

The real-time availability of SNOTEL data in recent years has increased the use of such data by private companies, industries, governments and researchers (NRCS). SNOTEL data have been used to categorize snowpack characteristics and trends of the Western U.S. For example, Cooley and Palmer (1997) analyzed daily SNOTEL data from 94 stations to detect similarities and differences in the accumulation and melt throughout the Western U.S., and found the accumulation potential, the decline in SWE (melt) potential, and a date range in peak SWE and melt out for each site. An analysis of SNOTEL data from 625 stations distributed across the mountains of the Western U.S. illustrated the regional similarities and differences in mountain snowpacks (Serreze et al. 1999). Subsequently, Serreze et al. (2001) used SNOTEL data to understand the spatiotemporal characteristics of large snowstorm events across the Western United States. Snow climatologies have been developed for the stations in and around the Colorado River basin using the daily data (Fassnacht and Derry 2010).

Collocated SNOTEL April 1st SWE correlate well with measurements taken from snow course surveys with an R^2 ranging from of 0.87 to 0.93, suggesting a significant spatial relation among the two independent data sets (Serreze et al. 1999). Interpolation using SNOTEL station SWE data compared to snow course measurements across the Colorado River Basin highlighted the utility of the daily data, but also that the use of SNOTEL data in conjunction with snow course surveys could provide improvements to models (Dressler et al. 2006a).

SNOTEL data have been increasingly used to provide meteorological variables for models, basin-wide temperature, SWE interpolation, and model evaluation (Molotch et al. 2004, Fassnacht 2006, Richer 2009, Harshburger et al. 2012, Jin and Wen 2012, Kashipazha 2012, Leibowitz et al. 2012, Raleigh and Lundquist 2012). The increasing number of SNOTEL stations and the availability of the data have allowed for greater incorporation into water resources studies.

The data have also been used to understand the effects of climate change on the timing and quantity of snowpack and runoff (Peterson et al. 2000) and have illustrated that snowpack accumulation has been decreasing in many areas of the Western U.S. (Stewart et al. 2004). Across Colorado, the data were analyzed to determine trends in snowmelt and streamflow timing, showing a general warming trend in temperatures and a decrease in SWE values (Clow 2010). Clow (2010) developed predictive models with the SNOTEL data, and assessed the changes to the onset of melt as estimated by the passage of 20% of annual runoff volume (tQ_{20}) and middle of melt (50% of runoff volume denoted as tQ_{50}) compared to trends in precipitation and temperature. The model suggested a shift in the timing with an earlier onset of melt and middle of melt.

1.4 Research Objective

Expanding on the findings of Cooley and Palmer (1997) and the work from Clow (2010), the motivation of this study was to investigate the application of SNOTEL data in a predictive hydrologic model for headwater catchments. Specifically, the purpose of this study was to estimate runoff (Q_{100}) and components of the hydrograph, the date of the tQ_{20}, tQ_{50}, tQ_{80}

(timing of 80% of the annual runoff), and peak runoff (Q_{peak}) from hydro-meteorological data available from SNOTEL stations. Specifically the objectives of the research are as follows:

1. Determine the correlation between streamflow and hydro-meteorological variables (from SNOTEL station data),
2. Create a multivariate model to estimate streamflow runoff and the timing of several hydrograph components,
3. Calibrate and test the model, and
4. Test the transferability of the model to two other watersheds differing in catchment area and location.

CHAPTER 2: STUDY AREAS

Site selection for this study was based on four requirements. Firstly, the watershed was a headwater catchment in the Rocky Mountains of the Western United States with a snow dominated hydrology system. Secondly, the streamflow was unregulated, or naturalized streamflows were computed from available data with a gauging station at the outlet to the watershed. Thirdly, a SNOTEL station was located either in or adjacent to the basin. The study assumed the SNOTEL station was representative of the snow characteristics of the watershed of study (Bohr and Aguado, 2001). Finally, the SNOTEL and stream gauging stations had accurate, complete datasets each with a long period of record, specifically spanning 33 water years, i.e., October 01, 1979 through September 30, 2012.

Joe Wright Creek watershed, with a drainage area of 8.8 km^2, is located in the Medicine Bow Mountains of north central Colorado (Figure 2.1), and was utilized in the model development and evaluation. The Joe Wright SNOTEL station is located in the center of the watershed (Figure 2.1). The USGS stream gauging station in located upstream of the Joe Wright Creek Reservoir; the creek receives additional water from the Michigan Ditch (MICDCPCO) which is a trans-basin water diversion owned and operated by the City of Fort Collins and monitored by the Colorado Division of Water Resources (CDWR).

To test the transferability of the models, two additional watersheds with larger drainage areas were selected (Table 1). Booth Creek watershed has an area of 16.0 km^2 and is located in the Gore Range Mountains of central Colorado (Figure 2.1). The USGS gauging station on Booth Creek is located upstream of the confluence with Gore Creek; the watershed is unregulated, with only natural lakes occurring in the higher elevations. The SNOTEL station is located adjacent to the Booth Creek Watershed. Shell Creek is the largest watershed with an area of 59.8km^2 and is located in the Big Horn Mountains of north central Wyoming (Table 2.1). The USGS gauging station is located upstream of the Shell Creek Reservoir, and it is also unregulated with only natural lakes occurring in the higher elevations. The SNOTEL station is located adjacent to the watershed, near the stream gauging station.

The SNOTEL stations are located in a similar elevation range around 3,000 meters, with the outlet of the watersheds varying more, having a mean elevation of 2,870 meters (Table 2.1). Additionally, the vegetation types within each of the headwater basins are similar with coniferous vegetation (*Pinus contorta*, *Picea engelmannii*, *Abies lasiocarpa* and *Pseudotsuga menziesii*) in the lower to mid elevations and alpine areas at the higher elevations (Figure A4.1). Booth Creek has more occurrences of deciduous trees (*Populus tremuloides*) in the lower elevations. While there is more variability in the annual SWE, precipitation and cumulative runoff from year to year in the two Colorado watersheds than at Shell Creek, the climatology of the two Colorado sites is similar (Table 2.1). Joe Wright Creek receives 18% more precipitation than Booth Creek and experiences on average a Q_{peak} of 6% higher. Booth Creek, however, experiences 27% higher runoff (Q_{100}) than Joe Wright Creek. Shell Creek watershed receives less precipitation, 36% less precipitation than Joe Wright Creek, lower observed runoff (44% less than Booth Creek) with noticeable less year to year variability in the SWE, precipitation and cumulative runoff (Table 2.1, Figure 2.2, Figure 2.3, Figure A1.1).

Table 2.1: Summary information of the SNOTEL station, USGS stream gauging station, watersheds characteristics and catchment hydro-climatology for the Joe Wright Creek, Booth Creek, and Shell Creek watersheds.

	Joe Wright Creek, CO			Booth Creek, CO			Shell Creek, WY		
SNOTEL Station									
Station name	Joe Wright			Vail Mountain			Shell Creek		
Station number	05J37S			06K39S			07E23S		
Elevation (m)	3,085			3,139			2,920		
Latitude (°N)	40.32			39.62			44.50		
Longitude (°W)	105.53			106.38			107.43		
USGS Gauging Station									
Gauge name	Joe Wright Creek above Joe Wright Reservoir			Booth Creek above Minturn, CO			Shell Creek above Shell Creek Reservoir		
Gauge number	06746095			09066200			06278300		
Gauge elevation (m)	3,045			2,537			2,758		
Gauge latitude (°N)	40.54 N			39.65 N			44.51 N		
Gauge longitude (°W)	105.88 W			106.32 W			107.40 W		
CDWR station	Michigan Ditch at Cameron Pass (MICDCPO)			N/A			N/A		
Watershed									
Basin area (km^2)	8.8			16.0			59.8		
Elevation range (m)	3,045 – 3,675			2,537 – 3,960			2,758 – 3,500		
Vegetation cover	Mixed coniferous forest, Alpine			Mixed deciduous and coniferous forest, Alpine			Mixed coniferous forest, Alpine		
Hydro-Climatology									
	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
Annual Peak SWE (mm)	1,331	366	690	996	284	637	752	328	472
Cumulative precipitation (mm)	1,636	789	1,129	1,369	577	927	871	467	723
Annual specific runoff (mm)	924	219	524	1,059	309	663	673	267	461
Annual peak runoff (mm)	32	5	16	35	5	17	35	10	20

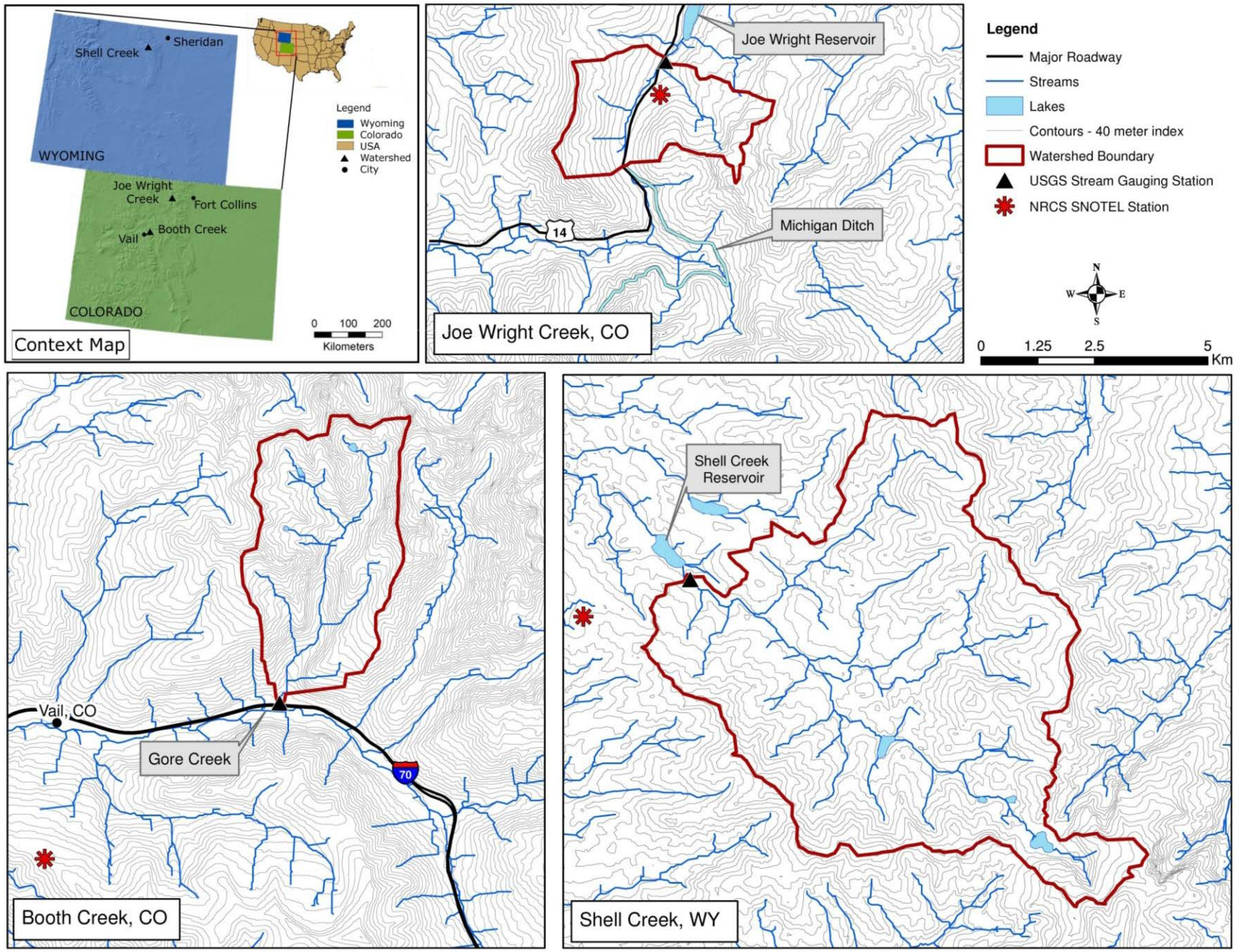

Figure 2.1: Topographic maps of the Joe Wright Creek, CO, Booth Creek, CO and Shell Creek, WY watersheds (Source: nationalamp.gov).

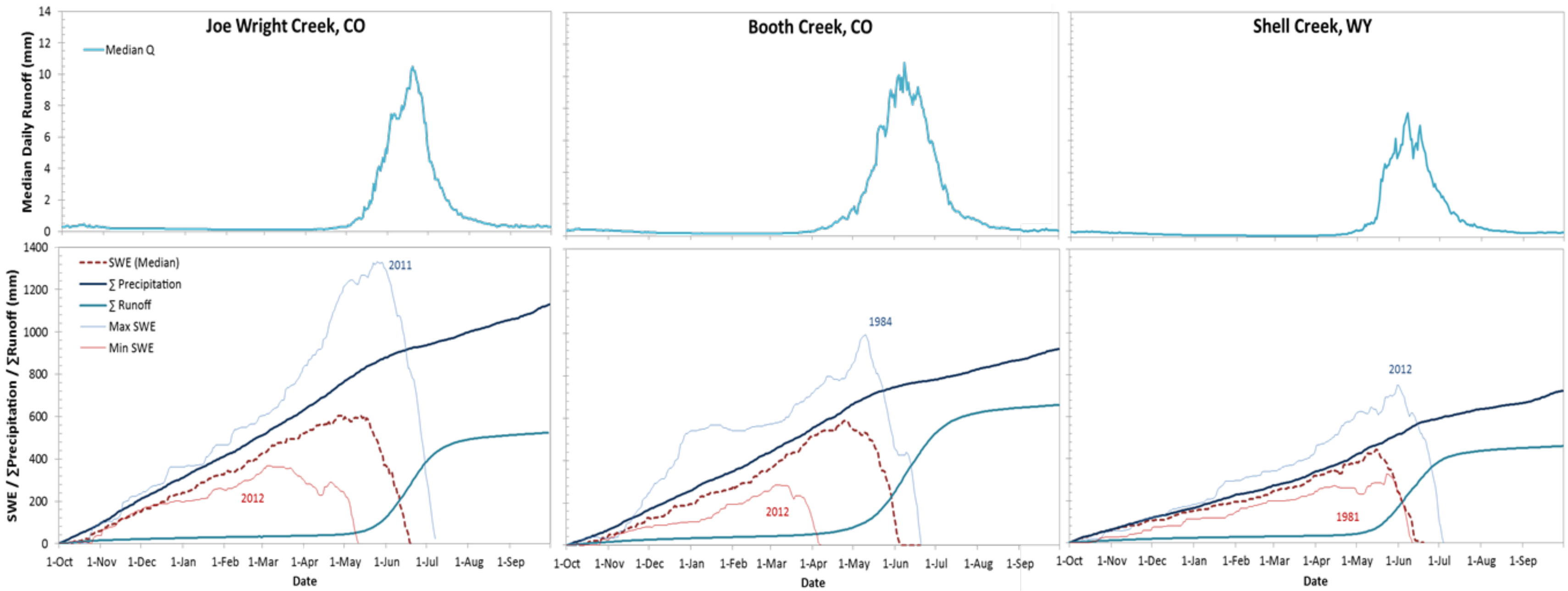

Figure 2.2: Summary of the catchment hydrology for the Joe Wright Creek, Booth Creek and Shell Creek watersheds. Upper plots are the median daily runoff at the USGS stream gauging stations for each of the watersheds. Lower plots are the cumulative precipitation (solid dark blue) and cumulative runoff (solid light blue), as well as the median daily SWE (dashed red), the maximum SWE year (thin blue line) and minimum SWE year (thin red line) to show the variability in the snowfall at each of the watersheds.

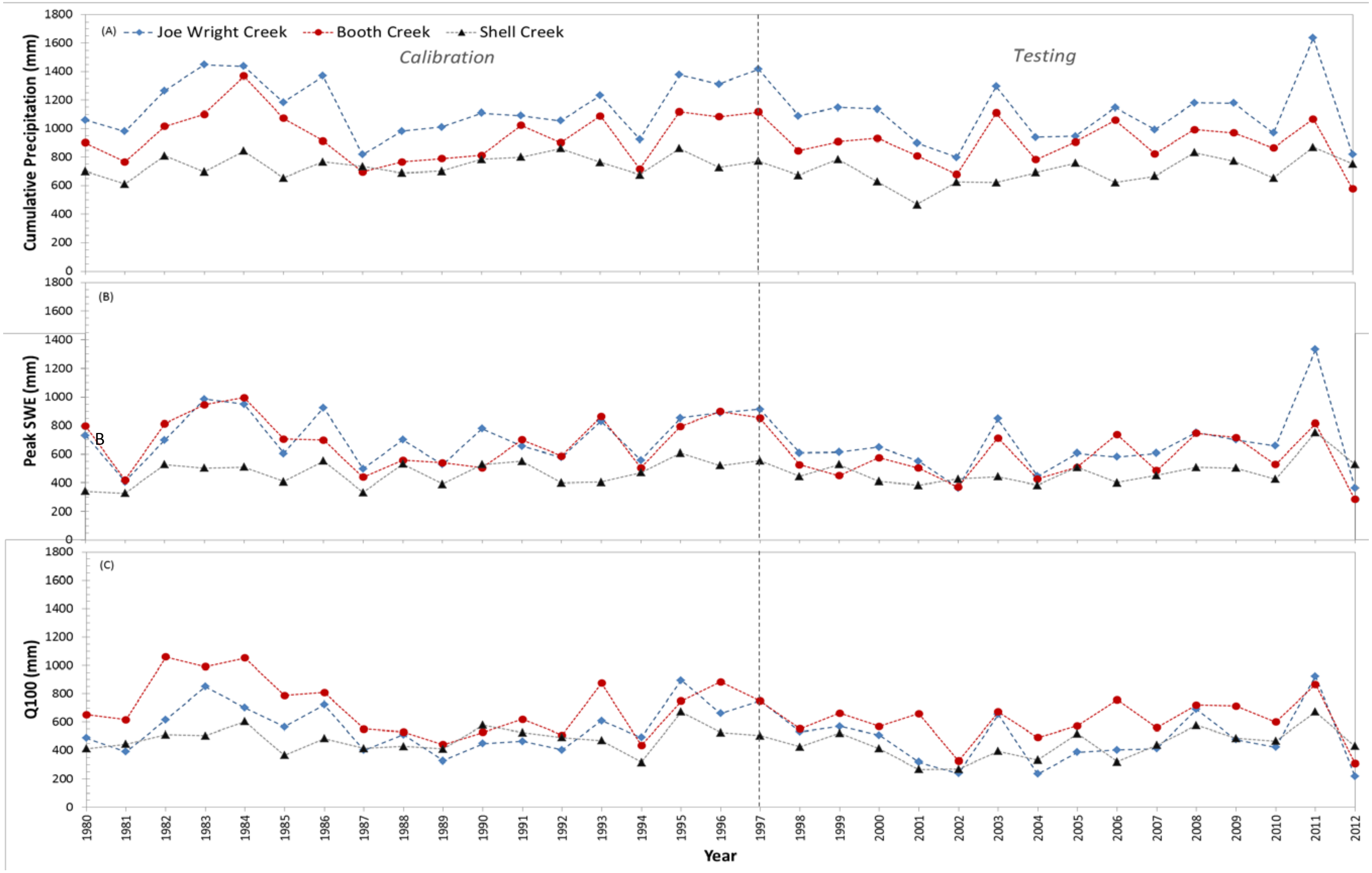

Figure 2.3: Time series of the a) cumulative precipitation b) peak SWE and c) Q_{100} for the Joe Wright Creek (dashed blue diamond), Booth Creek (dotted red circle), and Shell Creek (solid black triangle) watersheds from the 1980 to 2012 water years. The calibration (1980 to 1996) and testing (1997 to 2012) periods are noted on the figure.

CHAPTER 3: DATA AND METHODOLOGY

3.1 Data

The Natural Resource Conservation Service (NRCS) SNOTEL data and United States Geological Survey (USGS) streamflow data are available online at *http://www.wcc.nrcs.usda.gov/snow/* and *http://waterdata.usgs.gov/co/nwis/rt*, respectively. Using the daily time step interval, the available data for each of the three watersheds were downloaded for all water years from 1980 through 2012, organized into a dataset and analyzed. Streamflow data from the Michigan Ditch (MICDCPO) that flows into Joe Wright Creek were obtained from the Colorado Division of Water Resources (CDWR) (*http://www.dwr.state.co.us/*). All stations metadata were reviewed for understanding of station precision and maintenance record. The daily data were screened for missing values, errors and anomalies (Serreze et al. 1999). In the event of a day with a missing value, error value or an anomaly, an average value were gathered from the preceding and following day and used as a surrogate. Due to the high quality assurance and quality control standards by the NRCS, USGS and CDWR, there were no modifications to the variables specific to this study.

Booth Creek and Shell Creek watersheds are unregulated, but the streamflow at the Joe Wright Creek gauging station required naturalized flows. This was achieved by subtracting the flows from the CDWR Michigan Ditch from the Joe Wright flows to yield naturalized streamflow values. At the time of this current study, the 2012 water year streamflows from both the USGS (at all three watersheds) and the CDWR were classified as "provisional" and therefore are subject to change. It is assumed that these provisional data are representative of the 2012 conditions.

3.1.1 Temperature Data

Since the variable selection for the models was based on the Joe Wright SNOTEL and streamflow data, the presence of stationarity or non-stationarity (e.g., Milly et al., 2008), i.e., temporal trends, was evaluated. This station was part of the "orange" central northern Colorado station grouping defined by Clow (2010) that included five other SNOTEL stations (Roach, Willow Creek Pass, Stillwater Creek, Phantom Valley, Lake Irene). For this group over the period from approximately 1978 through 2007, there was a significant decrease (at the 5% confidence level) in April 1st SWE (12 to 27 mm per decade), as well as an earlier onset of snowmelt (2 to 4 days per decade) and timing of the snowmelt hydrograph (from streamflow data at multiple locations). As well, Clow (2010) reported a significant monthly warming in this area for all months except February, September and October, and the median temperature increased across the entire state was 0.7 degrees Celsius per decade. However, the snow climatology for only four of these stations were the same, with the Stillwater Creek and Phantom Valley stations being in different groupings derived with the SNOTEL data using self-organizing maps (Fassnacht and Derry, 2010).

From the Joe Wright SNOTEL data, the average annual air temperature was warming significantly at a rate of 1.1 degrees Celsius per decade for the entire period of record (1990 to 2012) and 1.2 degrees Celsius per decade from 1990 to 2007 (the period that Clow used). Annual maximum and minimum air temperatures were also significantly warming, at a rate of 1.4 and 1.0 degrees Celsius per decade, respectively. The months that are significantly warming at Joe Wright are the same as those that Clow (2010) found for the grouping of stations.

The SNOTEL temperature data demonstrated heterogeneity in the time series from 1990 to 2012 (Figure 3.1). The cause of the temporal trends in the temperature data is uncertain. Joe Wright SNOTEL station metadata (sensor data history) detailed on 12 May 2005 the temperature sensor was updated with new instrumentation (NRCS). In addition, the sensor was relocated within the SNOTEL site. The instrumentation change corresponds to the shift shown in Figure 3.1 during the 2005 season, especially in the maximum temperature for 2005. Since the model development was based on the Joe Wright Creek watershed, the problematic temperature data was not used in the model development.

However, of the other hydro-climatic variables, only tQ_{20} and tQ_{80} were becoming significantly earlier (4.8 and 4.1 days per decade, respectively), and that was only for the period that Clow (2010) used, i.e., 1980 to 2007. For the entire period (1980 to 2012), these trends were not significant. Thus the period of record is important (e.g., Venable et al., 2012); for the full period of record, all the variables, except temperature, showed stationarity. Also, the temperature data had the shortest period of record of all variables. Therefore, it was decided that the temperature data would not be used in this analysis.

3.2 Variables

Five components of hydrograph (tQ_{20}, tQ_{50}, tQ_{80}, Q_{100} and Q_{peak}) were chosen as the dependent variables for the models (Table 3.1). The independent hydro-meteorological variables (Table 3.1) were divided into three time periods for use in the model runs, capturing the time of peak SWE, at the end of melt-out when SWE reached zero at the snow pillow, and at the end of the water year.

3.3 Analysis

3.3.1 Correlation of Streamflow to Hydro-meteorological Data

Linear regression analyses were conducted to correlate the Joe Wright catchment streamflow to the independent hydro-meteorological variables. Determination of the strongest correlations between the streamflow data and the SNOTEL station data provided the foundation for model development.

3.3.2 Peak SWE and Melt Season Indices

The independent variables were derived on an annual basis for the water year, and during the melt period to focus on snowmelt driven runoff. The specific melt period was assessed annually for each watershed. This period reflected when snowmelt starts, from the date of last peak SWE to the time when snow was no longer present on the SNOTEL snow pillow. This melt time period varied inter-annually as well as among the study watersheds.

3.3.3 Model Selection

To generate a predictive-type model, the tQ_{20}, tQ_{50}, tQ_{80} and Q_{peak} model runs focused only on variables (Table 3.1) that could be measured or known at the time of peak SWE, since the timing of the Q_{20}, Q_{50}, Q_{80} and Q_{peak} generally occurred during or shortly after melt-out of the snowpack at the SNOTEL station. The Q_{100} was modeled at both the time of peak SWE and at the time of melt-out, with the former to match the estimation of other variables and the latter to refine the total runoff estimation once snow melt concluded. The most correlated variables for the Joe Wright Creek watershed provided the variables that were used in multiple model configurations. The correlated independent variables were tested for multicollinearity through a Variance Inflation Factor (VIF) (Leamer 1973, Fox and Monnette 1992). Variables with a VIF greater than fiver were considered highly collinear and were eliminated as an optimal model. Ultimately, a series of model configurations were conducted on the Joe Wright Creek watershed to determine the optimal models.

3.3.4 Calibration and Testing

The data set was divided into two time periods, a 17-year calibration period (1980 to 1996) and a 16-year testing period (1997 to 2012). The data for the calibration period were run through a multiple linear regression analysis to derive equation coefficients, and then the models were evaluated for the testing period.

3.3.5 Model Evaluation

The performances of the various models were evaluated using the coefficient of determination (R^2) and the Nash-Sutcliffe coefficient of efficiency (NSCE) (Equation 1) (Martinec and Rango 1986, Richard and Gratton 2001, Richer 2009):

$$NSCE = 1 - \frac{\sum_{i=1}^{n}(Xi - Xi')^2}{\sum_{i=1}^{n}(Xi - \bar{X})^2} \qquad (1),$$

where X is the measured dependent value (e.g., annual runoff or Q_{100} for a specific year *i*), X' is the simulated dependent value, $\bar{X}$ is the mean dependent, and *n* is the number of values. The results were analyzed to identify the highest NSCE and R^2 values to assist the determination of the optimal model configuration to estimate tQ_{20}, tQ_{50}, tQ_{80}, Q_{100} and Q_{peak} for Joe Wright Creek.

3.4 Optimal Model Application

The optimal model configurations generated at the Joe Wright Creek watershed for the five dependent variables/hydrograph components were then applied to the Booth Creek and Shell Creek watersheds. Using the same methods as applied to Joe Wright Creek, the data from the two larger watersheds were used to generate basin specific coefficients for the calibration period (1980 to 1996) and then evaluated for the testing period (1997 to 2012) using the NSCE and R^2 evaluations.

3.5 Joe Wright Creek Model Transferability

In a final evaluation of the Joe Wright Creek model performance, the transferability of the models for that watershed were tested by applying them to the larger two watersheds. The observed independent variables from the two watersheds were inserted into the optimal Joe Wright models to estimate tQ_{20}, tQ_{50}, tQ_{80}, Q_{100} and Q_{peak}, and then evaluated using the NSCE and R^2 evaluations.

Table 3.1: Table of the hydro-meteorological variables and their corresponding description. The variables are divided by the dependent variables and the variables available in subsequent order to the timing of the water year, at peak SWE, at melt out of snow on the snow pillow, and at the end of the water year.

	Variable	Description
Dependent Variables	tQ_{20}	The date (timing) of the 20th percentile on cumulative discharge curve
	tQ_{50}	The date (timing) of the 50th percentile on cumulative discharge curve
	tQ_{80}	The date (timing) of the 80th percentile on cumulative discharge curve
	Q_{100} at Peak SWE	Value for the cumulative runoff forecasted at the date of the Peak SWE observed at the SNOTEL Station
	Q_{100} at Melt Out	Value for the cumulative runoff forecasted at the date of the snowpack melt out as observed at the SNOTEL station
	Q_{peak}	Forecasted value for the maximum daily discharge for a given water year observed at the USGS stream gauging station
At Peak SWE	April 1st SWE	The SWE at the SNOTEL station on April 1 of each year.
	Peak SWE	The maximum accumulation of SWE at the SNOTEL station.
	Date of Peak	The corresponding date of Peak SWE, signaling the onset of snowmelt with no later peaks and the continuous decline in SWE recorded at the snow pillow.
	Number of days with snow on the ground to date of peak	The number of consecutive days with an accumulated snowpack (SWE>0) observed at the SNOTEL station beginning at the start of the water year up to the Date of Peak SWE
At Melt Out	Number of melt days	The number of positive melt days that occur from the Date of Peak SWE to the day of zero snow remaining on the snow pillow at the SNOTEL station (melt period specific).
	Total number of days with snow on the ground	The number of consecutive days with an accumulated snowpack (SWE>0) observed at the SNOTEL station beginning at the start of the water year and concluding at the end of the snow melt season (melt period specific).
	Last day with snow on the ground (date of melt out)	Observed date when the SWE value on the snow pillow reach zero (SWE = 0). Due to site and watershed characteristics, this value does not necessarily reflect the last day with snow of the ground in the watershed (melt period specific).
	Mean daily change in SWE (loss to snowpack) during melt	Also considered the daily melt. The average daily change in SWE values observed on the at the SNOTEL station. Represents water leaving the snowpack as a positive melt value (melt period specific).
	Number of days of with positive snow melt	The total number of days between the Date of Peak SWE and the date in which the snowpack has melted out (SWE = 0) at the SNOTEL snow pillow (melt period specific).
End of Water Year	Cumulative precipitation	The sum of daily precipitation observations at the SNOTEL station
	Percentage of precipitation as snow	The portion of the precipitation that falls as snow in the watershed. The ratio of the Peak SWE from the SNOTEL station compared to the cumulative precipitation value.
	Cumulative runoff (Q_{100})	The sum of daily runoff observations from the USGS gauging stations. Presented as a depth of water (mm) over the entire watershed
	Mean daily discharge during melt	The mean daily observed runoff at the USGS stream gauging stations during the season specific melt period (from the date of peak SWE to the last day with snow of the ground).
	Date Peak Runoff	The date of the greatest mean daily runoff observed at the USGS stream gauging stations.

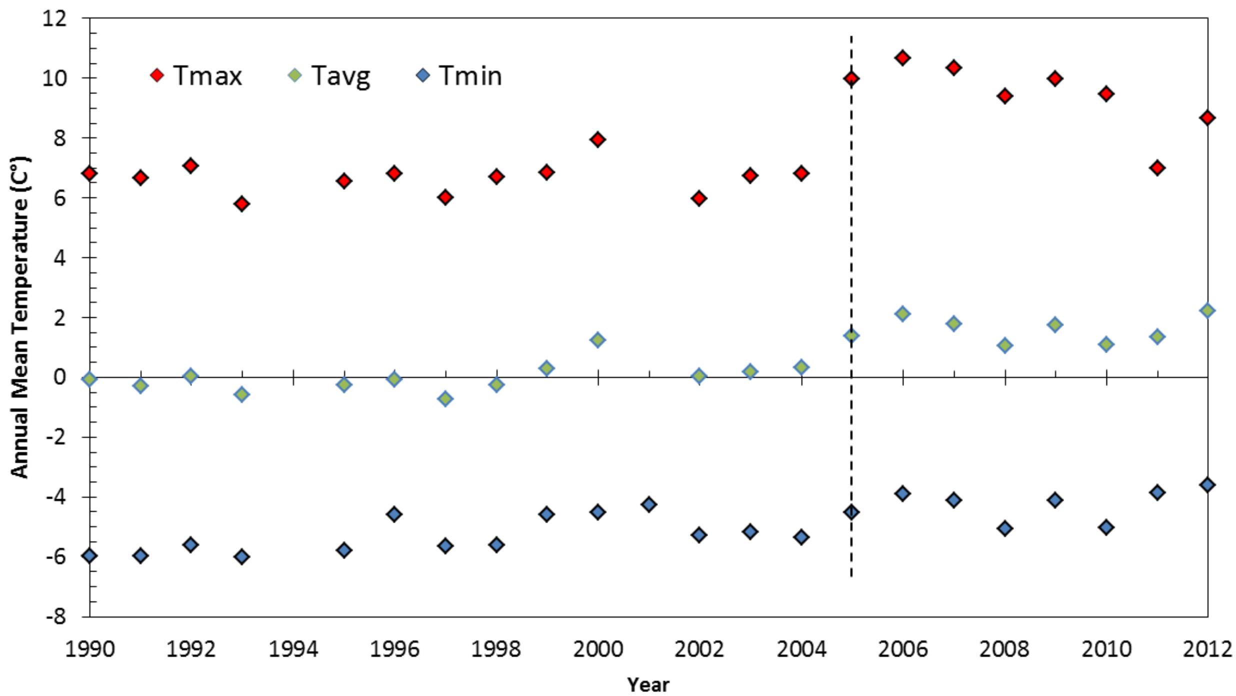

Figure 3.1: Temperature data from the Joe Wright Creek SNOTEL station from 1990 to 2012. The maximum temperature is in red, the average temperature in green, and the minimum temperature in blue. Note the noticeable “shift” in the temperature data beginning in 2005, as identified with the dashed vertical line. Temperature data was partial or missing for 1994 and 2001.

CHAPTER 4: RESULTS

4.1 Correlation of Hydro-meteorological Data to Streamflow

There was an overall strong positive correlation between streamflow and the snowpack variables derived from the SNOTEL SWE data at Joe Wright Creek (Table 4.1). The variables available at the time of Peak SWE , i.e., April 1st SWE, peak SWE, date of peak, and the number of days with snow on the ground up to peak, consistently had R^2 values ranging from 0.19 to 0.58. Peak SWE was the most correlated variable with a mean R^2 value of approximately 0.57, and was most correlated to the tQ_{50} dependent variable (Table 4.1). Variations in the R^2 values for the calibration and testing periods were minimal with the exception of April 1st SWE which had an 1160% stronger correlation during the testing period.

The R^2 values from the melt period variables, i.e., number of melt days, number of days with snow of ground, last day of snowpack on the ground, mean daily change in SWE (melt) and average runoff during melt shown in Table 3.1 support a strong correlation to streamflow. The total number of days with snow on the ground, the last day with snow on the ground, and average runoff during the melt period had the greatest correlation to the hydrograph components (R^2 = 0.32 to 0.85). From all the considered variables, the date of last day with snow on the ground was most correlated to tQ_{50} (R^2 = 0.85). The number of melt days was not well correlated to the dependent variables of streamflow (R^2= 0.00 to 0.04). The deviation in the R^2 values between the calibration period and the testing period had a 20% difference among the variables, with greater accuracy in the testing period (excluding the poorly correlated variable of the number of melt days).

The end of the water year variable of cumulative precipitation, was highly correlated to streamflow (R^2 = 0.60). Among this strongly correlated variable, there was a 16% increase in R^2 values from the calibration to the testing period. The percentage of precipitation falling as snow was less correlated to streamflow (R^2 = 0.20 to 0.40). There was a 70% decrease in correlation during the calibration period than the testing period.

4.2 Model Development

Up to eight model configurations with differing variables were conducted to determine the optimal model configuration. Table 4.2 shows the model matrix identifying the model run number and the independent variables that were used during model trials. The independent variables were analyzed for collinearity through an analysis of the Variance Inflation Factor (VIF). The VIF results illustrated a wide range of low to high collinearity among the independent variables (Table 4.3). Model configurations that expressed a VIF of greater than five were considered strongly collinear and not utilized in the optimal model selection. As the models incorporated additional variables the collinearity tended to increase, especially with peak SWE and the estimated Q_{100} being used as a dependent variable. The simulated Q_{100} had the greatest VIF (greater than 20) in each of model runs, suggesting greater collinearity to the independent variables. At the time of melt-out, independent variables had higher collinearity with the VIF being consistently greater than five. The evaluation of the model trials suggests the majority of the model configurations performed well. Of the 68 total model outcomes, a total of 15 had NSCE values of less than 0.50. Of those 15 only three outcomes were less than zero (Table 4.4). With the exception of the Q_{peak} trials, the model run outcomes experienced strong correlation values consistently explaining on average 66% of the variance. The optimal model runs were selected for each of the five dependent variables based on utilizing the fewest and least-multicollinear independent variables while maintaining the greatest NCSE and R^2 values at the calibration and testing periods. Summarized in Table 4.4, the optimal model run for tQ_{20} was selected as model run three ($NSCE_{testing}$ = 0.59), the tQ_{50}, tQ_{80} and Q_{100} at peak SWE were selected as model run two ($NSCE_{testing}$ = 0.55, 0.32 and 0.83 respectively), the Q_{100} at melt out was selected as model run six ($NSCE_{testing}$ = 0.84) and the Q_{peak} model run was selected as model run three ($NSCE_{testing}$ = 0.52). The least performing optimal model run was tQ_{80} ($NSCE_{testing}$ = 0.32). It is important to note that while the results for the Q_{100} at melt-out are strong, the independent variables in the optimal model run express strong collinearity (Table 4.3).

4.3 Optimal Model Run

The selected model configurations were applied to the three watersheds. Basin specific coefficients (Table 4.5) were then generated during the calibration period and applied to the testing period. The optimal models performed well when applied to the Joe Wright Creek, Booth Creek and Shell Creek watersheds. The positive relations among the observed and simulated dependent variables during the calibration and testing period are illustrated in Figure 4.1. The timing of the Q_{20}, Q_{50} and Q_{80} had similar results with confined clustering along the one to one line. The results of the optimal model run for the tQ_{50} had greater accuracy than tQ_{20} and tQ_{80}. In comparing the watersheds, Shell Creek's results were less accurate with greater residuals; smaller values were overestimated while larger values were underestimated.

Evaluation from the optimal model runs supports the accuracy of the models (Table 4.6). In 26 of the 36 model trials the NSCE value were greater than 0.50. In only 10 cases were the values less than 0.50, of which only one was less than zero. Additionally the R^2 values demonstrated a strong correlation among the calibration and testing period with values on average consistently greater than 0.62. There was a consistent, although minimal, decrease in modeling performance from the onset of melt (tQ_{20}) to the end of the melt period (tQ_{80}). The testing period of the model runs performed slighter better than the calibration period. The best performing model was the Q_{100} at melt-out in each of the watersheds (NSCE = 0.62 to 0.94), though the variables expressed stronger collinearity. The Q_{peak} and tQ_{80} model trails were found to have the weakest performing models. NSCE and R^2 values were consistently lower in both the calibration and testing periods and well as from watershed to watershed. While Joe Wright watershed generally had a slightly better performance, the overall model applications to each watershed performed well with few exceptions. The results of the Q_{peak} were mostly the lowest of all the model dependent variables (NSCE = 0.23 to 0.55, R^2 = 0.22 to 0.64). The Q_{peak} model run in the Booth Creek watershed was a weak performing model ($NSCE_{calibration}$ = 0.23; $NSCE_{testing}$ = 0.35), while the tQ_{80} model application in the Shell Creek watershed was found to be the least accurate of the optimal model runs ($NSCE_{calibration}$ = 0.15; $NSCE_{testing}$ = -0.03).

4.4 Optimal Model Transferability

Transferability of the Joe Wright Creek watershed model configurations and coefficients resulted in range of model performances (Figure 4.2). The R^2 values for both watersheds had consistently strong correlations, with 10 of the 12 values being greater than 0.70. However, the

NSCE values had a greater range of variability and an overall weaker performance, with values ranging from -3.17 to 0.47. Shell Creek watershed outperformed Booth Creek watershed when using the Joe Wright Creek models. The Q_{100} both at peak SWE and at melt-out in the Shell Creek watershed resulted in the strongest performance of the models (NSCE= 0.46 and 0.47 respectively). A consistent result of using the Joe Wright Creek watershed models in the larger two watersheds was the inability for the model to estimate the range of variability seen in the dependent variables. As such, the resulting slopes were less than the one to one line (<1) in 83% of the model runs. Q_{peak} model runs simulated significantly less variability than what was observed.

Table 4.1: Correlation of the hydro-meteorological variables to dependent variables of the tQ_{20}, tQ_{50}, tQ_{80}, Q_{100} and the Q_{peak} from the Joe Wright Creek watershed. The R^2 value, slope and y-intercept are shown for all years (1980-2012). Furthermore, the calibration period (1980 to 1996) and the testing period (1997 to 2012) values are shown for comparison.

		All years (1980 – 2012)			**Calibration (1980 – 1996)**			**Testing (1997 – 2012)**		
	Variable	R^2	Slope	Y-inter.	R^2	Slope	Y-inter.	R^2	Slope	Y-inter.
tQ_{20}	peak SWE	0.51	0.04	41027.4	0.41	0.05	41026.1	0.62	0.04	41028.5
	date of peak	0.47	0.44	22842.2	0.40	0.49	20763.9	0.53	0.39	24873.2
	days with snow up to peak	0.35	0.34	40989.1	0.22	0.32	40995.7	0.49	0.34	40987.6
	April 1st	0.28	0.05	41028.3	0.06	0.03	41044.2	0.61	0.07	41018.7
	# of melt days	0.00	-0.01	41057.5	0.01	0.37	41045.7	0.02	-0.24	41063.4
	# days with snow	0.37	0.46	40944.1	0.32	0.48	40941.7	0.40	0.42	40951.9
	last day snow	0.62	0.77	9597.6	0.72	0.91	3799.8	0.52	0.62	15415.0
	Mean delta SWE	0.45	1.64	41024.2	0.32	1.67	41025.1	0.60	1.55	41024.3
	Avg runoff at melt	0.55	2.91	41040.5	0.43	2.87	41042.6	0.69	2.85	41038.9
	Sum of P	0.50	0.04	41009.3	0.51	0.05	41004.7	0.49	0.04	41014.3
	Sum of Q	0.56	0.05	41031.0	0.54	0.06	41027.7	0.55	0.04	41033.5
	% Precip as snow	0.30	76.42	41011.2	0.07	41.63	41034.3	0.65	99.42	40995.9
tQ_{50}	peak SWE	0.58	0.03	41051.7	0.55	0.04	41048.3	0.62	0.03	41053.8
	date of peak	0.55	0.36	26230.0	0.52	0.42	23852.1	0.58	0.32	28078.1
	days with snow up to peak	0.44	0.29	41018.1	0.32	0.28	41020.1	0.57	0.28	41018.3
	April 1st	0.29	0.04	41053.6	0.07	0.02	41064.4	0.58	0.05	41046.8
	# of melt days	0.02	0.23	41067.0	0.00	0.13	41072.5	0.02	0.22	41065.8
	# days with snow	0.55	0.42	40971.5	0.41	0.40	40977.6	0.69	0.43	40969.6
	last day snow	0.85	0.67	13403.6	0.84	0.73	11049.6	0.87	0.62	15558.6
	Mean delta SWE	0.39	1.14	41052.6	0.36	1.31	41050.0	0.42	1.00	41054.3
	Avg runoff at melt	0.51	2.11	41063.5	0.50	2.28	41063.6	0.53	1.92	41063.3
	Sum of P	0.60	0.03	41036.2	0.66	0.04	41030.8	0.54	0.03	41041.1
	Sum of Q	0.63	0.04	41054.7	0.60	0.04	41052.2	0.64	0.04	41056.4
	% Precip as snow	0.30	57.88	41040.8	0.12	39.22	41053.2	0.54	69.90	41032.6
tQ_{80}	peak SWE	0.45	0.03	41071.3	0.35	0.03	41072.6	0.55	0.03	41071.0
	date of peak	0.35	0.29	29271.0	0.24	0.27	29996.6	0.46	0.28	29783.3
	days with snow up to peak	0.24	0.21	41050.1	0.09	0.15	41065.1	0.41	0.23	41043.6
	April 1st	0.19	0.03	41074.4	0.02	0.01	41088.6	0.45	0.04	41066.3
	# of melt days	0.04	0.36	41078.6	0.03	0.40	41079.7	0.03	0.27	41079.5
	# days with snow	0.36	0.34	41008.5	0.22	0.28	41025.7	0.51	0.36	41001.7
	last day snow	0.68	0.59	16651.8	0.61	0.59	16754.2	0.74	0.56	17985.0
	Mean delta SWE	0.23	0.87	41074.6	0.11	0.70	41080.1	0.33	0.88	41072.4
	Avg runoff at melt	0.32	1.65	41082.7	0.25	1.55	41085.4	0.39	1.62	41080.6
	Sum of P	0.50	0.03	41056.6	0.47	0.03	41057.4	0.53	0.03	41057.8
	Sum of Q	0.52	0.04	41073.3	0.40	0.03	41075.1	0.60	0.03	41073.0
	% Precip as snow	0.20	46.70	41064.1	0.05	24.08	41080.0	0.40	58.81	41054.9

		All years (1980 – 2012)			**Calibration (1980 – 1996)**			**Testing (1997 – 2012)**		
	Variable	R^2	Slope	Y-inter.	R^2	Slope	Y-inter.	R^2	Slope	Y-inter.
Q100	peak SWE	0.79	0.04	41027.4	0.69	0.05	41026.1	0.87	0.04	41028.5
	date of peak	0.43	0.44	22842.2	0.40	0.49	20763.9	0.43	0.39	24873.2
	days with snow up to peak	0.43	0.34	40989.1	0.49	0.32	40995.7	0.37	0.34	40987.6
	April 1st	0.47	0.05	41028.3	0.12	0.03	41044.2	0.83	0.07	41018.7
	# of melt days	0.01	-0.01	41057.5	0.00	0.37	41045.7	0.01	-0.24	41063.4
	# days with snow	0.56	0.46	40944.1	0.69	0.48	40941.7	0.45	0.42	40951.9
	last day snow	0.70	0.77	9597.6	0.69	0.91	3799.8	0.69	0.62	15415.0
	Mean delta SWE	0.64	1.64	41024.2	0.57	1.67	41025.1	0.68	1.55	41024.3
	Avg runoff at melt	0.74	2.91	41040.5	0.66	2.87	41042.6	0.82	2.85	41038.9
	Sum of P	0.84	0.04	41009.3	0.77	0.05	41004.7	0.89	0.04	41014.3
	Sum of Q	1.00	0.05	41031.0	1.00	0.06	41027.7	1.00	0.04	41033.5
	% Precip as snow	0.40	76.42	41011.2	0.18	41.63	41034.3	0.60	99.42	40995.9
Q_{peak}	peak SWE	0.54	0.02	0.6	0.31	0.02	4.1	0.73	0.02	-1.1
	date of peak	0.47	0.23	-9382.7	0.45	0.24	-9942.8	0.48	0.21	-8628.5
	days with snow up to peak	0.47	0.20	-23.8	0.50	0.22	-27.0	0.43	0.18	-20.3
	April 1st	0.24	0.03	2.7	0.00	0.00	17.1	0.68	0.04	-6.6
	# of melt days	0.01	-0.12	20.9	0.05	-0.37	31.6	0.00	-0.07	17.6
	# days with snow	0.48	0.27	-49.6	0.57	0.29	-55.1	0.39	0.23	-42.4
	last day snow	0.58	0.38	-15423	0.57	0.38	-15420.6	0.55	0.36	-14803.4
	Mean delta SWE	0.54	0.92	-2.2	0.34	0.79	1.1	0.70	0.95	-3.6
	Avg runoff at melt	0.75	1.75	6.2	0.62	1.59	8.1	0.88	1.82	4.9
	Sum of P	0.56	0.02	-9.6	0.48	0.02	-7.1	0.62	0.02	-10.6
	Sum of Q	0.72	0.03	1.0	0.72	0.03	0.6	0.71	0.03	1.5
	% Precip as snow	0.29	38.45	-6.8	0.02	10.71	11.1	0.70	58.13	-19.4
	Date of PeakQ	0.17	0.23	-9393.1	0.30	0.30	-12245.6	0.09	0.16	-6507.2

Table 4.2: Matrix of correlated hydro-meteorological variables used for model run development. Check marks represent the model run included the corresponding variable. Empty boxes reflect the corresponding variable was not used in that model configuration.

	Correlated Variables	**Model Run**							
		1	2	3	4	5	6	7	8
		tQ* Q_{100} Q_{peak}	tQ* Q_{100} Q_{peak}	tQ* Q_{100} Q_{peak}	tQ* Q_{100} Q_{peak}	tQ* Q_{100} Q_{peak}	tQ* Q_{100} Q_{peak}	tQ* Q_{100} Q_{peak}	tQ* Q_{100} Q_{peak}
At Peak SWE	Peak SWE	☑☑☑	☑☑☑	☑☑☑	☑☑☑	☑☑☑	☑☑☑	☑☑☐	☐☑☐
	Date of Peak	☑☑☐	☑☑☑	☑☑☑	☑☑☑	☑☑☐	☑☑☑	☑☑☐	☐☐☐
	Number of Days with Snow on Ground to Peak	☐☐☐	☑☑☐	☑☐☑	☑☑☑	☐☑☐	☑☑☐	☐☑☐	☐☐☐
	April 1 SWE	☐☐☐	☐☐☐	☑☑☐	☑☑☑	☐☑☐	☐☑☐	☑☑☐	☐☐☐
	Forecasted Q100	☐☐☐	☐☐☐	☐☐☐	☑☐☐	☑☐☑	☑☐☑	☑☑☐	☐☐☐
At Melt-Out	Average Runoff during Melt	☐☐☐	☐☐☐	☐☐☐	☐☐☐	☐☑☐	☐☑☐	☐☑☐	☐☑☐
	Last day with Snow on Ground (melt out)	☐☐☐	☐☐☐	☐☐☐	☐☐☐	☐☐☐	☐☑☐	☐☑☐	☐☑☐
	Mean Daily change in SWE during Melt	☐☐☐	☐☐☐	☐☐☐	☐☐☐	☐☐☐	☐☐☐	☐☑☐	☐☑☐

tQ* = tQ_{20}, tQ_{50}, and tQ_{80}

Table 4.3: Matrix of the Variance Inflation Factor (VIF) for the model runs and their corresponding correlated hydro-meteorological variables. The numerical value identifies the respective VIF for the variable with greater values signifying greater multicollinearity. The dash line indicates that variable was not included in the corresponding model configuration (See Table 4.2). TQ* includes the tQ_{20}, tQ_{50} and tQ_{80}.

	Correlated Variables	**Model Run**																							
		1			2			3			4			5			6			7			8		
		tQ^*	Q_{100}	Q_{peak}	tQ^*	Q_{100}	Q_{peak}	tQ^*	Q_{100}	Q_{peak}	tQ^*	Q_{100}	Q_{peak}	tQ^*	Q_{100}	Q_{peak}	tQ^*	Q_{100}	Q_{peak}	tQ^*	Q_{100}	Q_{peak}	tQ^*	Q_{100}	Q_{peak}
At Peak SWE	Peak SWE	1.7	1.7	1.0	1.8	1.8	1.7	4.5	4.4	1.8	17.8	4.5	16.0	16.0	8.0	14.3	16.0	21.6	16.0	17.8	23.8	-	-	7.3	-
	Date of Peak	1.7	1.7	-	3.5	3.5	1.7	4.1	2.1	3.5	2.9	4.1	2.4	2.4	6.1	-	2.4	9.6	2.4	2.9	10.1	-	-	-	-
	Number of Days with Snow on Ground to Peak	-	-	-	3.4	3.4	-	3.4	-	3.4	0	3.4	0	-	3.7	-	0	3.9	-	-	4.0	-	-	-	-
	April 1 SWE	-	-	-	-	-	-	2.8	2.7	-	2.8	2.8	-	-	4.9	-	-	8.8	-	2.8	9.3	-	-	-	-
	Forecasted Q100	-	-	-	-	-	-	-	-	-	20.2	-	20.1	20.1	-	14.3	20.1	-	20.1	20.2	-	-	-	-	-
At Melt-Out	Average Runoff during Melt	-	-	-	-	-	-	-	-	-	-	-	-	-	9.3	-	-	10.1	-	-	13.5	-	-	5.8	-
	Last day with Snow on Ground (melt out)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10.3	-	-	12.6	-	-	6.7	-
	Mean Daily change in SWE during Melt	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.7	-	-	6.2	-

$tQ^* = tQ_{20}$, tQ_{50}, and tQ_{80}

Table 4.4: Nash-Sutcliffe coefficient of efficiency (NSCE) and Correlation strength (R^2) values for calibration and testing period of the model trial configurations.

	Model Run							
	1	2	3	4	5	6	7	8
tQ20								
NSCE (Calibration)	0.50	0.53	**0.59**	0.59	0.53	0.59	-	-
R^2 (Calibration)	0.49	0.52	**0.58**	0.58	0.52	0.52	-	-
NSCE (Testing)	0.65	0.59	**0.53**	0.59	-4.66	-4.66	-	-
R^2 (Testing)	0.65	0.59	**0.53**	0.65	0.68	0.68	-	-
tQ50								
NSCE (Calibration)	0.65	**0.68**	0.77	0.77	0.68	0.68	0.77	-
R^2 (Calibration)	0.65	**0.67**	0.77	0.77	0.68	0.68	0.77	-
NSCE (Testing)	0.63	**0.55**	0.51	0.51	0.56	0.56	0.51	
R^2 (Testing)	0.71	**0.66**	0.60	0.60	0.66	0.66	0.60	
tQ80								
NSCE (Calibration)	0.38	**0.44**	0.62	0.62	0.44	0.44	0.62	-
R^2 (Calibration)	0.37	**0.44**	0.62	0.62	0.44	0.44	0.62	-
NSCE (Testing)	0.45	**0.32**	0.06	0.06	0.32	0.32	0.06	-
R^2 (Testing)	0.60	**0.50**	0.38	0.38	0.50	0.50	0.38	-
Q100		At Peak SWE				At Melt-out		
NSCE (Calibration)	0.71	**0.75**	0.86	0.90	0.92	**0.94**	0.96	0.82
R^2 (Calibration)	0.71	**0.74**	0.85	0.90	0.93	**0.96**	0.90	0.82
NSCE (Testing)	0.84	**0.83**	0.71	0.71	0.76	**0.84**	-0.18	0.88
R^2 (Testing)	0.86	**0.86**	0.77	0.78	0.83	**0.90**	0.74	0.91
Qpeak								
NSCE (Calibration)	0.33	0.49	**0.55**	0.55	0.51	0.55	-	-
R^2 (Calibration)	0.31	0.47	**0.53**	0.53	0.49	0.53	-	-
NSCE (Testing)	0.64	0.60	**0.52**	0.52	0.58	0.52	-	-
R^2 (Testing)	0.73	0.63	**0.56**	0.56	0.63	0.56	-	-

Table 4.5: The calculated coefficients from the optimal model configurations at the Joe Wright Creek, Booth Creek and Shell Creek watersheds. Coefficients developed from the calibration period (1980 to1996) of the study

Dependent Variables	Coefficient of Independent Variables	Joe Wright	Booth Creek	Shell Creek
tQ20	Intercept	27545.5	-12519.1	11680.9
	Peak SWE	0.0616	0.0440	0.0352
	Date of Peak SWE	0.3298	1.3084	0.7160
	No. Days with snow on ground to Peak SWE	-0.1874	-0.6947	-0.1932
	April 1st SWE	-0.0455	-0.0208	0.0295
tQ50	Intercept	26521.8	16722.1	17482.8
	Peak SWE	0.0282	0.0301	0.0334
	Date of Peak SWE	0.3549	0.5942	0.5748
	No. Days with snow on ground to Peak SWE	-0.1363	-0.2572	-0.0966
tQ80	Intercept	29104.9	19689.6	36443.3
	Peak SWE	0.0292	0.0334	-0.0188
	Date of Peak SWE	0.2928	0.5222	0.1125
	No. Days with snow on ground to Peak SWE	-0.2343	-0.2346	0.1561
Q100	Intercept	38720.3	252380.9	-36879.6
(At Peak SWE)	Peak SWE	0.6312	0.9591	0.3625
	Date of Peak SWE	-0.9561	-6.1743	0.8965
	No. Days with snow on ground to Peak SWE	3.0848	4.9801	1.8885
Q100	Intercept	121050.7	195831.8	-137136.4
(At Melt Out)	Peak SWE	0.5235	0.6268	0.3645
	Date of Peak SWE	-8.5380	-8.7363	-3.2631
	No. Days with snow on ground to Peak SWE	3.2786	4.1741	1.1293
	April 1st SWE	-0.2686	-0.0013	-0.3345
	Average Runoff during Melt	33.343	31.518	14.998
	Date of last day with Snow on the Ground	5.5686	3.9406	6.6003
Qpeak	Intercept	-3133.6	-4077.0	-1127.7
	Peak SWE	0.0045	0.0090	0.0227
	Date of Peak SWE	0.0760	0.0995	0.0271
	No. Days with snow on ground to Peak SWE	0.1407	0.0355	0.1203

Table 4.6: Optimal model run accuracy and efficiency results for the Joe Wright Creek, Booth Creek and Shell Creek watersheds (corresponds to the results displayed in Figure 4.1).

	Joe Wright Creek				**Booth Creek**				**Shell Creek**			
	Calibration		Testing		Calibration		Testing		Calibration		Testing	
Dependent Variable	NSCE	R^2	NSCE	R^2	NSCE	R^2	NSCE	R^2	NSCE	R^2	NSCE	R^2
tQ20	0.59	0.58	0.59	0.64	0.56	0.56	0.54	0.62	0.69	0.69	0.63	0.62
tQ50	0.68	0.67	0.55	0.59	0.76	0.81	0.49	0.66	0.54	0.55	0.62	0.58
tQ80	0.44	0.44	0.32	0.50	0.71	0.77	0.45	0.56	0.15	0.14	-0.03	0.00
Q100 at Peak	0.75	0.74	0.83	0.86	0.74	0.79	0.59	0.67	0.52	0.52	0.38	0.66
Q100 at Melt Out	0.94	0.94	0.84	0.90	0.81	0.85	0.62	0.71	0.86	0.86	0.85	0.85
Qpeak	0.55	0.53	0.52	0.56	0.23	0.22	0.35	0.45	0.45	0.44	0.55	0.64

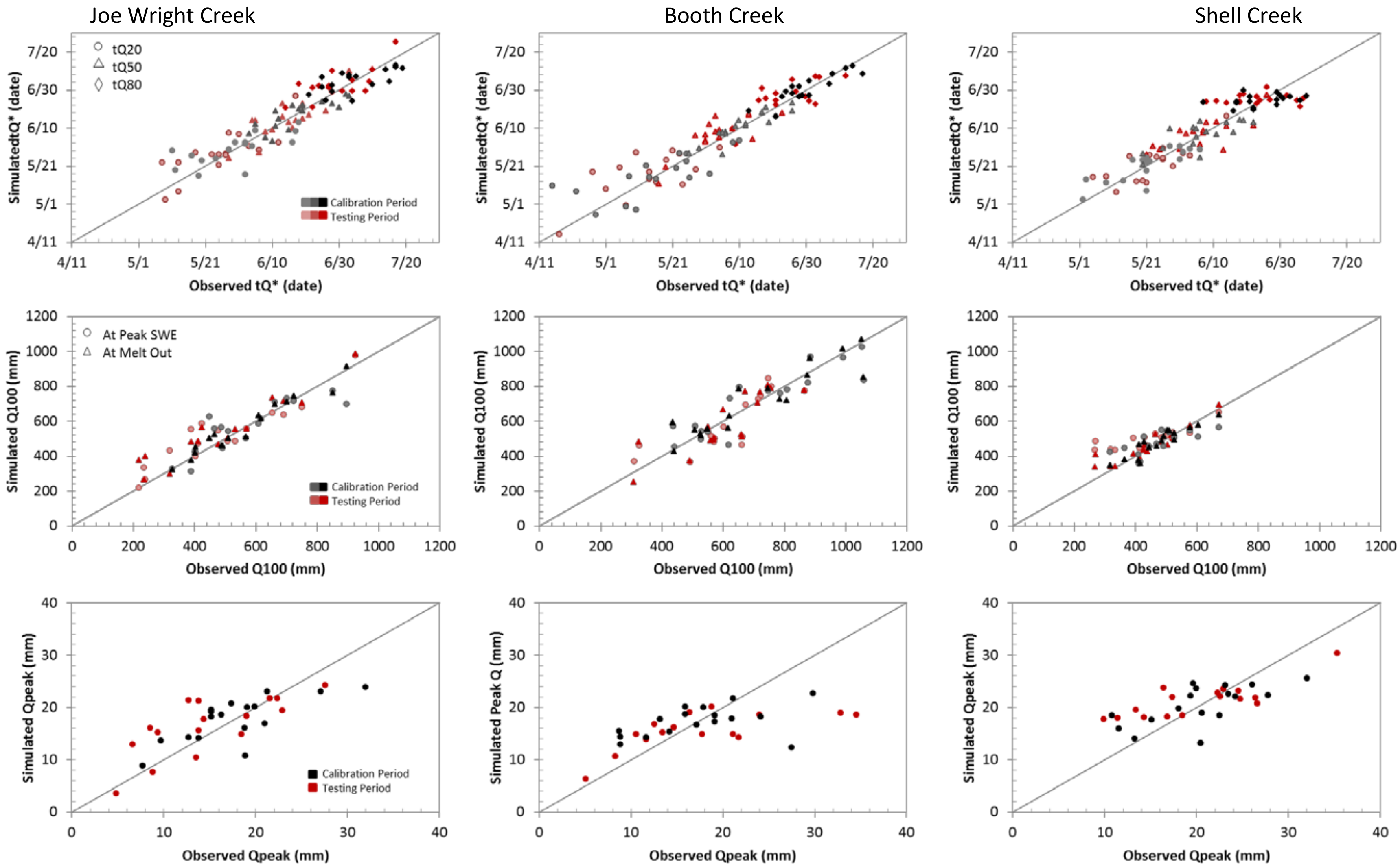

Figure 4.1: Results of the tQ*, Q_{100} and Q_{peak} dependent variables from the application of the optimal model configurations for the Joe Wright Creek, Booth Creek and Shell Creek watersheds. Model coefficients are basin specific for each of the three watersheds. Symbols in black represent the calibration period (1980 to 1996) of the model development and red symbols represent the testing period (1997 to 2012).

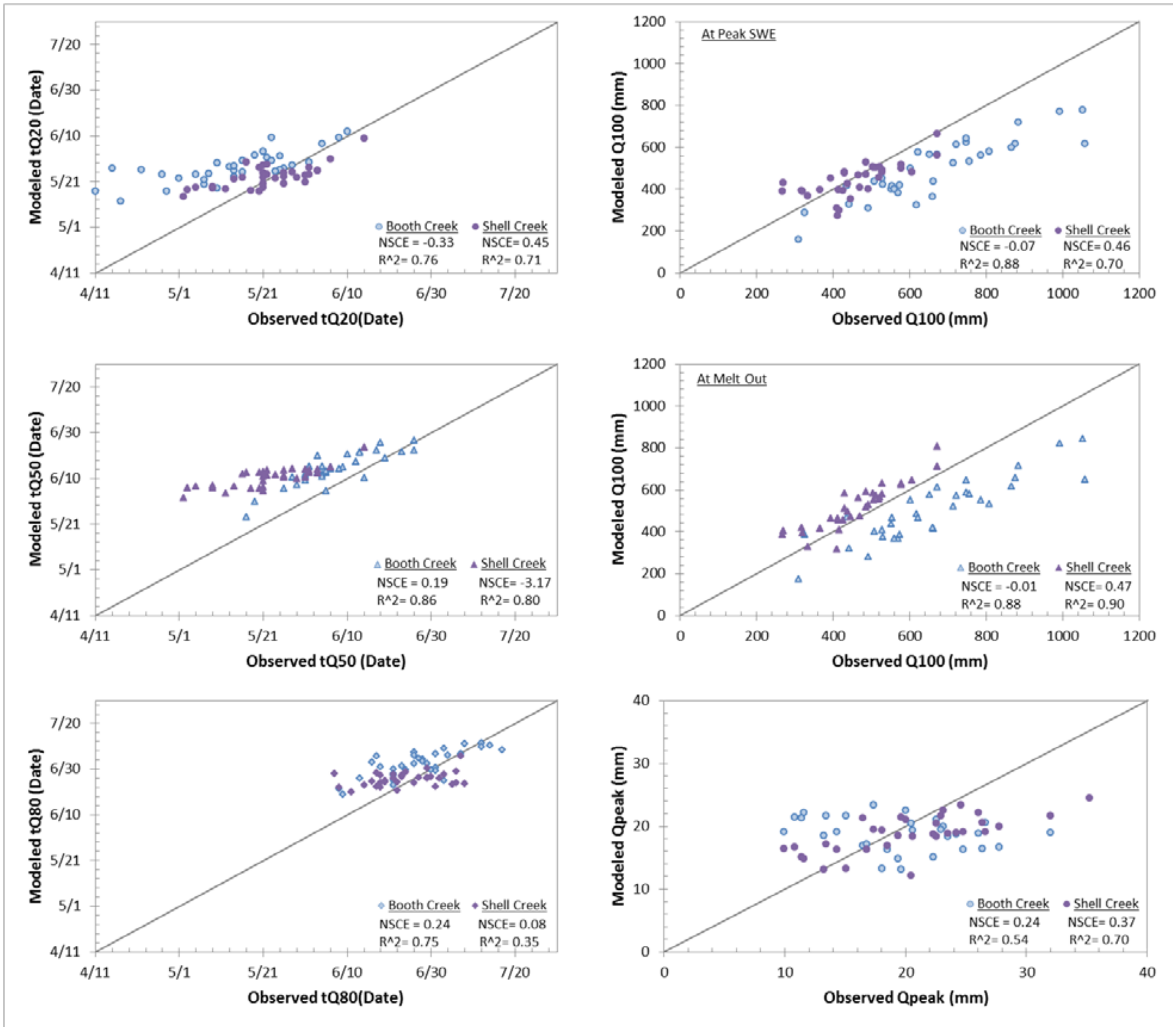

Figure 4.2: Results of the optimal model configurations as developed from the Joe Wright Creek watershed. Model coefficients are specific to Joe Wright Creek watersheds and have been applied to the larger Booth Creek (shown in blue) and Shell Creek (shown in purple) watersheds to test the transferability of the model application. The NSCE and R^2 values from the results are shown on their respective plot.

CHAPTER 5: DISCUSSION

The purpose of this study is to estimate runoff (Q_{100}) and components of the hydrograph, in particular, the date of the Q_{20} (tQ_{20}), Q_{50} (tQ_{50}), Q_{80} (tQ_{80}), and peak runoff (Q_{peak}), from the SNOTEL data. This study showed that SNOTEL stations can be used to estimate these components of the streamflow hydrograph; the models illustrate a means to use SNOTEL data to estimate streamflow for headwater basins. The SNOTEL data represent a point measurement (Kashipazha 2012); they can be used to represent the snowpack across an area, i.e., a watershed (Bohr and Aguado 2001). The SNOTEL data report continuously and provide more information in real-time than the monthly manual snow surveys (Bohr and Aguado, 2001).

5.1 Correlation to Streamflow

Cooley and Palmer (1997) established the concept of using additional variables from the SNOTEL data, compared to the snowcourse data in forecasting streamflow. Their interpolations of characterizing the SNOTEL data derived the accumulation and melt potentials and provided understanding of the range in peak SWE and melt out dates. Hydrological models have only used precipitation and temperature data from SNOTEL stations as inputs, and SWE data for comparison or assimilation (Dressler *et al*. 2006b; Clow *et al.* 2012). Clow (2010) showed significantly increasing temperatures of 1.2 degrees Celsius, thus the non-stationarity of the temperature data may limit the accuracy or applicability of models that incorporate such data, especially if other variables are stationary. No other studies were found to use additional variables derived from SNOTEL data (Table 3.1) for use in streamflow forecasting.

As expected peak SWE was strongly correlated to streamflow since this correlation, traditionally made with April 1st SWE as a surrogate for peak SWE, has been the basis for water supply outlooks since the initial forecast were made in the earlier 1900's (Garen 1992, Pagano and Garen 2006). With SNOTEL stations, the actual peak SWE can be captured, rather than just using the manually measured April 1st SWE; on average across the Western U.S. SWE on April 1st was 12% less than the actual peak SWE, occurring before or after April 1st (Bohr and Aguado 2001). While the snowpack at lower elevation or lower latitude sites typically peak prior to April 1st (Fassnacht 2006), the lower correlation using April 1st SWE (Table 4.1) can mainly be attributed to the additional precipitation that accumulates, usually as snow, in the headwater catchments after April 1st. This is especially true for Colorado and Wyoming, which receive a greater portion of snow accumulation later in the winter and in early spring (Serreze *et al*. 2001); the mountains near the Front Range of Colorado, such as Joe Wright receives substantial upslope events in March and April during El Niňo years. This iterates the benefit of having automated real-time SNOTEL stations.

The highest correlation was associated with the tQ_{50} dependent variable. The melt-out period variables were also highly correlated to the streamflow characteristics as tQ_{50} demonstrated the greatest R^2 value for the date of last day with snow on the ground. The strong correlation could be associated with the close proximity in time to the Q_{50} and the end of the melt period at a SNOTEL station. The limited variation among the calibration and testing period suggests there is less variability in melt variables than variables for the prior period. The calibration period at Joe Wright Creek experienced more frequent wet years with larger snowpacks than the testing period (Figure 2.3, Figure A1.1). The greater peak SWE and later peak SWE dates are associated with more precipitation and a delayed melt season (Cooley and Palmer 1997). The delayed onset to melt slightly decreased the correlation of the hydro-meteorological variables during the calibration period. The drier testing period with slightly smaller snowpacks and earlier onsets to melt (Q_{20}) had greater correlation due to the closer proximity in the timing of tQ_{20} and tQ_{50} as well as Q_{peak}.

The high correlation to the end of the year variables is associated with the dependent variables inherent relation to the amount of precipitation a watershed receives. In years with abundant precipitation it can be expected that there would likely be an increase in runoff with more water moving through the system (Figure 2.2, Figure 2.3, Figure A1.1).

5.2 Model Development and Configuration

In developing the models, the strongest correlated variables with minimal collinearity among the independent variables were selected to configure an optimal model (Garen 1992, Fassnacht 2006, Clow 2010). The model trials performed well with the optimal models being selected from their low collinearity (Table 4.3) and the results of the Nash-Sutcliffe coefficiency of efficiency (NSCE) and the R^2 values (Table 4.4). The tQ_{20} model was selected with four variables (Table 4.2) which produced the best model configuration. The tQ_{50}, tQ_{80}, Q_{100} (at peak SWE) and Q_{peak} all incorporated the same three variables (peak SWE, date of peak SWE, and number of days with snow on the ground up to peak SWE). There were additional variables incorporated into the model's configuration that resulted in the same results but with greater collinearity among the variables. Therefore, the models with the fewest and least collinear variables and strongest evaluations were selected for the model development. The tQ_{80} that also considered the end of snowmelt had the weakest performing model. The poor model performance could be associated with the lag time in melt waters reaching the streamflow as well as any additional melting snowpack in the watershed after melt-out at the SNOTEL station, which is typically at a low elevation in the watershed (Figure A2.1 - A4.1). The runoff time lag and additional snowpack contributing to the streamflow vary depending on the amount SWE remaining in the watershed and how much of the catchment is still snow covered. Incorporating Snow Covered Area data into the model could improve the later tQ_{80} models (Richer 2009).

5.3 Optimal Model Run

Overall the models performed very well (Figure 4.3 and Table 4.6). As expected the Q_{100} at melt-out resulted in the best model. The incorporation of variables associated with the snowmelt period as well as snowmelt runoff strongly influenced the cumulative runoff from each watershed. Melt indices of the timing of the 20%, 50% and 80% of the total annual stream flow are commonly used to approximate the onset of melt (tQ_{20}), the middle of melt or centroid of runoff (tQ_{50}), and the end of snowmelt (tQ_{80}) (Peterson 2000, Richer 2009, Clow 2010). The tQ_{20} model performed well for Joe Wright Creek and Shell Creek but slightly poorer for Booth Creek. The weaker performance in Booth Creek is representative of the earlier onset on melt (tQ_{20}) and the ultimately a longer melt season (Figure 2.2, Figure A1.1). Booth Creek begins melt (tQ_{20}) on average 8 days before Shell Creek and fourteen days earlier than at Joe Wright Creek. The middle of melt (tQ_{50}) and the end of melt (tQ_{80}) are similar at Booth Creek and Shell Creek, with melt at Joe Wright Creek occurring on average 8 days later for both the tQ_{50} and

tQ_{80}. Booth Creek has greater range in elevation, with a lower gauge elevation (2,500 m) as well as a more southerly aspect and steeper slopes (Figure A2.1 - A4.1). As such, the physiographic characteristics of the catchment could be conducive to earlier snowmelt than the other watersheds. Joe Wright Creek watershed has moderate slopes up to 30% with dividing east and west aspects and a mix of coniferous and alpine land cover (Figure A2.1 - A4.1). The catchment receives more precipitation and snowfall than Booth Creek and Shell Creek (Figure 2.1 and 2.2). Shell Creek receives less precipitation overall, with a high percentage of alpine land cover, gentler slopes and a dominant northern aspect (Figure A2.1 - A4.1). As a result both Shell Creek and Joe Wright Creek watersheds experience a delayed onset to melt (tQ_{20}), with short wave radiation strongly influencing melt later in the spring. (Table 2.1, Figure 2.1, Figure A1.1).

The implications on a shorter runoff period are that water managers need to plan for and capture the runoff in greater quantities over a shorter time period. The timing of the runoff can have implications with water right owners and water uses. A shorter runoff period could trigger the need for great water storage to capture the high flows while being able to satisfy water rights. With the model runs performing well overall, the tQ_{80} model application to Shell Creek did not perform well (NSCE = -0.03 to 0.15). Additionally, the Q_{peak} values in the Booth Creek watershed demonstrated poor model performance (NSCE = 0.23 to 0.35) (Figure 4.2). In these two cases the models fail to account for the greater variability of the independent variables associated with the peak runoff and the timing of the Q_{80} (Figure 4.2).

5.4 Optimal Model Transferability

In five of the six cases the transferred model overestimated values less than average and underestimated values more than average, i.e., a regression between observed and simulated values had a slope was less than one. The simulated models estimated less variability than was observed. The results demonstrate the inefficiency to adequately estimate the extreme events, such as in Q_{100}, and Q_{peak}. The two most recent years present interesting contrasts; 2011 was the wettest year on record while 2012 was the driest year on record in Colorado (Figure 2.2, Figure 2.3, Figure A1.1). The two extreme years were difficult to simulate at the Colorado sites since they deviated so greatly from the mean (Figure 2.2, Figure 2.3, Figure A1.1).

The Joe Wright Creek models fit better to Shell Creek than Booth Creek, with model result deviations due to physiographic and climatic differences (Figure A2.1 - A4.1). While there is variation in the coefficients due to the difference in the watersheds, some of the coefficients at the Shell Creek are close with those at Joe Wright Creek (Table 4.5). The greatest differences by less than a factor of five were from the date of peak, illustrating greater variability in date of peak SWE among the three watersheds. Similarly, there was as greater difference in the average runoff for the Q_{100} at melt-out between Shell Creek and the two Colorado watersheds since Shell Creek usually has less annual runoff (Q_{100}); 14% less than Joe Wright Creek and 44% less than Booth Creek (Figure 2.2, Figure 2.3). The models performed better when applied to other watersheds with similar variability in the independent variables. The Joe Wright Creek models accounts for the greater variability in the precipitation and runoff. When applied to the

Shell Creek site in Wyoming that has less variability in inter-annual precipitation, the model performs more poorly.

The three watersheds have different physiographic characteristics (Table 2.1, Figure 2.1, Figure A2.1 - A4.1). Booth Creek has a greater range of elevation, nearly twice that of Shell Creek, steeper slopes, and streamflow to the southwest, while Shell Creek flows west and Joe Wright Creek flows north. The more southerly watershed also has some differing vegetation with deciduous and mixed forests at the lower elevations. As such, the initial melt out at lower elevations generates an earlier tQ_{20} and an overall longer melt season compared to the other two watersheds (Figure 2.2). Joe Wright Creek and Shell Creek both have shorter melt periods than compared to Booth Creek by nine and 12 days, respectively. The tQ_{50} and the tQ_{80} are similar for the three headwater catchments, demonstrating similar timing for the middle and end of melt.

While the SNOTEL SWE data (Figure 2.2, Figure 2.3, Figure A1.1) illustrate similar SWE patterns, Booth Creek has more runoff than the other two basins (Figure 2.2). As discussed above, these differences could be a result of physiographic, vegetation and soil properties; however the Vail Mountain SNOTEL station is located outside of the Booth Creek watershed (Figure 2.1) and may be less representative of the basin than the other SNOTEL stations are of their watershed. This basin abuts the western side of the Continental Divide on the windward side of the range, exposing the watersheds to greater frequencies of orographic precipitation. As a result the basin may receive more precipitation or blowing snow inputs than recorded at the Vail Mountain SNOTEL station.

While the cumulative runoff for all three basins is similar, there is greater variability in the two Colorado watersheds, depicting greater variability in the precipitation across each watershed. It is likely that Colorado experiences more large scale climatic influences, such as the El Niño Southern Oscillation, while the impact of the Pacific Decadal Oscillation is lesser in northern Wyoming. As a result of the greater variability in precipitation, there is more variability in the inter-annual peak SWE, cumulative runoff, and timing of the melt indices (Q_{20}, Q_{50}, and Q_{80}). As such, the Joe Wright model performs better in like headwater catchments.

5.5 Study Limitations

While the models produce reasonable estimates, there are limitations. The site selection of using a headwater catchment with an unregulated and gauged creek was challenging. The hydrology of many streams across the mountainous Western U.S. has been altered by human development. The great demand for water has created a history of water projects including diversions and storage, yielding few unregulated gauged basins or the associated naturalized flows with an associated SNOTEL station, each of which having a longer (30+ year) period of record.

Additionally, the assumption of a SNOTEL site being representative of the entire watershed may not as appropriate in such a study (Kashipazha 2012). The variability of the snowpack can differ significantly throughout a watershed. While the precipitation and snowpack characteristics may vary throughout the watershed from year to year, there are numerous consistencies across a watershed that allow point data to represent an entire watershed; the point data can be used as an index for the area rather than a direct measure of what occurs over the area. Vegetation remains generally unchanged from year to year, with the exception of disturbances, such as beetle kill, forest fires and forest harvesting. Changes in the terrain, in particular slope, aspect and elevation, are negligible over time, with the exception of catastrophic geological events; such events have not occurred over the period of instrument record. Therefore, the physiographic variables that drive the meteorological forcing's across a watershed can be considered constant over an annual basis.

5.6 Implications to Water Resources

Traditional streamflow forecasts produce a quantitative volume of water over a specified period of time, such as April 1st through September 30th (Pagano *et al*. 2004). The additional estimation of various streamflow components provides for more detail on the seasonal hydrograph. Supplementing the Q_{100} estimation with the tQ_{20}, tQ_{50}, tQ_{80}, and Q_{peak} provides further information that can be used to construct and refine a seasonal hydrograph. The models presented in this study illustrate what streamflow could look like, aiding in more accurate streamflow forecasts. Being able to estimate the streamflow components is important for water managers, water right holders, water users and recreational outfitters.

The successful forecast of the tQ_{20} could help establish when water managers begin storing runoff in reservoirs. On the recreational side, it could allow rafting outfitters to plan and prepare for their season with more confidence. Additionally knowing the onset of snowmelt in snow dependent regions could aid in the agricultural decision making processes for farmers and ranchers. The successful forecasting of the tQ_{50} could aid in water planners to know when the center of mass of runoff has occurred and assist in their reservoir management plans.

While tQ_{80} was less successfully estimated, the potential of knowing such information would be instrumental for reservoir managers and water commissioners to begin releasing stored water in order to satisfy downstream water rights holders and water users. The prediction of the cumulative runoff (Q_{100}) would be instrumental to all water users. While the estimates of peak runoff (Q_{peak}) were less efficient, the forecasts are important for emergency management, environmental planners and recreational outfitters.

Finally, if climate change causes warmer temperatures and a decrease in the amount of winter precipitation (Knowles *et al.* 2006, Clow 2010), successfully modeling a possible shift in the timing of the onset of melt and the central timing (Q_{50}) could be beneficial for the future of management of the limited changing water resources.

5.7 Future Work

With snowpack characteristics varying spatially and temporally across a watershed (Fassnacht 2006), especially across different elevations, it becomes practical to integrate multiple measurement sites within a model. Incorporating more point measurements into models would provide more representative snowpack measurements (Dressler *et al.* 2006a), especially since SNOTEL measurements often over-estimate the snowpack in a watershed (Daly *et al*. 2000) and the surrounding area (Kashipazha 2012, Meromy *et al*. in press). Additionally, with the year to year variability in some watersheds, it may be useful to develope individual models that focus on extreme (i.e., wet and dry) years (e.g., 2011 and 2012).

Additional hydro-meteorological variables could be incorporated into streamflow models. The apparent warming trend in the SNOTEL temperature data should be investigated further as the rates are almost an order of magnitude more than the global average. Newer enhanced SNOTEL station instrumentations could provide more information about snowpack and snowmelt characteristics, including soil temperature and moisture data, solar radiation data, and snowpack density derived using the snow depth sensors implemented in the last eight years.

CHAPTER 6: CONCLUSIONS

Hydro-meteorological variables from SNOTEL stations were strongly correlated with streamflow at the Joe Wright Creek watershed. The variables were analyzed based on the following three periods: at the time of peak SWE, melt-out of the snowpack on the snow pillow, and at the end of the water year. Peak SWE had the strongest relation to streamflow, and the greatest correlation to tQ_{50}. At snowpack melt-out and end of the water year, variables were also strongly correlated to streamflow with average runoff during melt, last day with snow on the ground and cumulative precipitation having the greatest correlations to streamflow. Since SNOTEL temperature data expressed non-stationarity they were not used in this study.

A multivariate model was successfully created at Joe Wright Creek to accurately estimate runoff (Q_{100}) and components of the hydrograph, specifically, the date of the Q_{20} (tQ_{20}), Q_{50} (tQ_{50}), Q_{80} (tQ_{80}), and peak runoff (Q_{peak}). Selected models were tested with multiple variable configurations to develop optimal models for each of the dependent variables. Six models were generated: five models for streamflow estimates at the date of peak SWE and an additional refined estimate of streamflow for the Q_{100} at melt-out.

The modeling period was divided into 1980 to 1996 for calibration and 1997 to 2012 for testing. Model variables were analyzed for collinearity and evaluated using the Nash-Sutcliffe coefficient of efficiency (NSCE) and the coefficient of determination (R^2). Most of the models (78%) had a NSCE value greater than 0.50 during both the calibration and testing periods. The accuracy of the models were greatest for Q_{100} at melt-out (NSCE = 0.82) followed by the Q_{100} at peak SWE, tQ_{50} and tQ_{20}, with a NSCE of 0.64, 0.61 and 0.60 respectively. The Q_{peak} model accuracy was modest (NSCE = 0.44) while the tQ_{80} was the least accurate (NSCE = 0.36). The optimal model from Joe Wright Creek was used to test the validation and transferability to the two larger watersheds: Booth Creek, CO and Shell Creek, WY.

The optimal models were modified to generate basin specific coefficients for Booth Creek and Shell Creek. The resulting streamflow estimates had mostly accurate, with 72% of the outcomes having a NSCE value greater than 0.5. The greatest accuracies were the tQ_{20}, tQ_{50}, and Q_{100} components of the hydrograph, with the tQ_{80} and Q_{peak} models being less accurate. The application of the models to the other headwater basins demonstrated the successful streamflow estimation with the incorporation of basin specific coefficients.

The Joe Wright Creek model direct transferability to the other two watersheds failed to be as successful. While the R^2 values showed strong correlation in the modeled versus observed values (R^2 = 0.35 to 0.90), the NSCE values illustrated the poorer performance. The only exception was Shell Creek's result for the Q_{100} at peak SWE and melt-out with a NSCE of 0.46 and 0.47, respectively). The weak results suggested the hydro-climatology of the three watersheds differ enough from one another to null the application of the Joe Wright Creek specific equations to other headwater basins.

Overall, the optimal model equations did produce good streamflow estimates for the other watersheds once new coefficients were determined. The study supports the use of basin specific coefficients derived from SNOTEL data as a beneficial tool to estimate hydrograph components. SNOTEL data are available in real-time and can thus be used to develop models to go beyond the seasonal streamflow volume forecast, estimating additional components of the hydrograph. These findings are important for expanding the traditional water supply forecasts for water resource managers, recreational outfitters, water right holders and other water users in the Western United States.

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APPENDIX I: WATERSHED HYDROLOGY

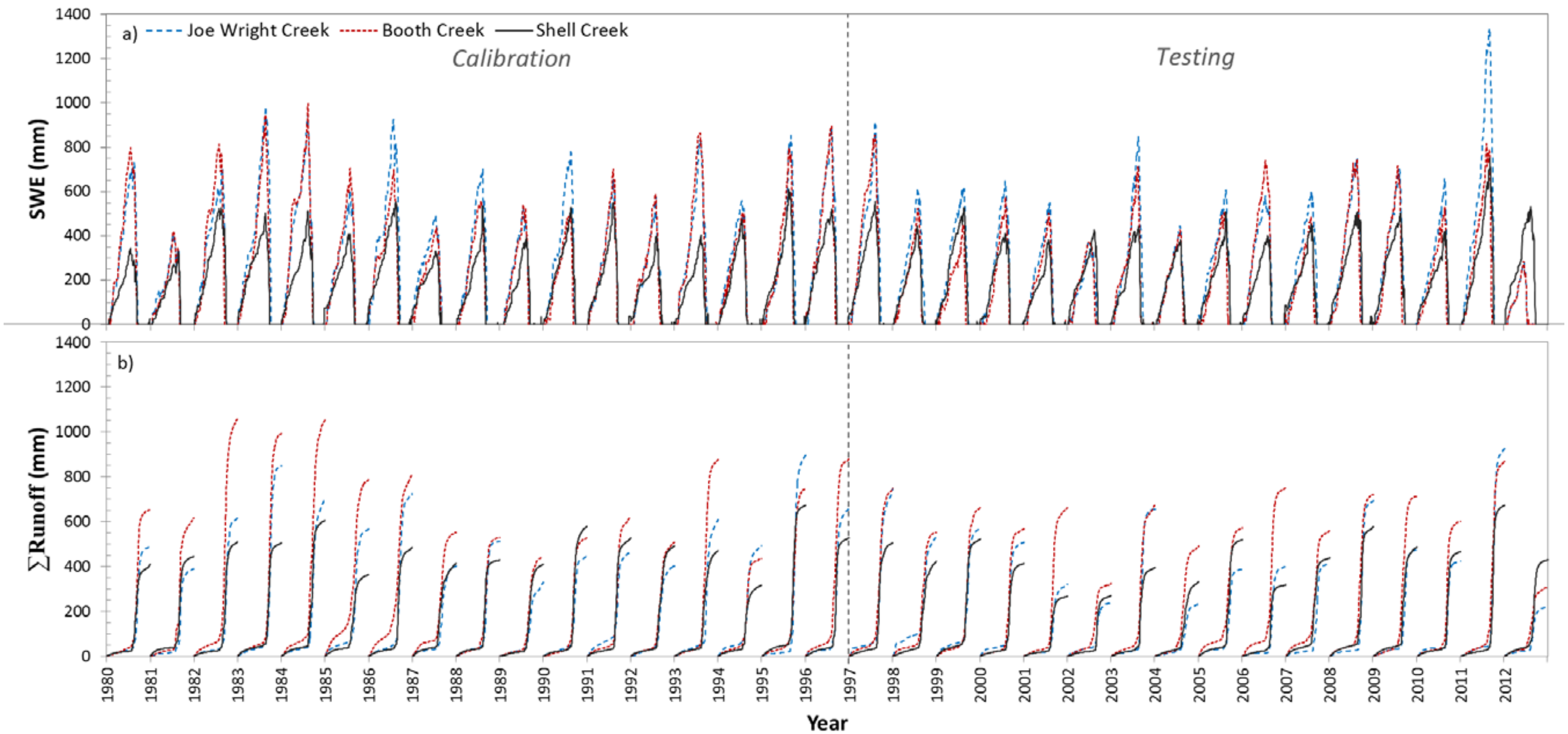

Figure A1.1: Time series of the a) SWE b) cumulative runoff for the Joe Wright Creek (dashed blue), Booth Creek (dotted red), and Shell Creek (solid black) watersheds from the 1980 to 2012 water years. The calibration (1980 to 1996) and testing (1997 to 2012) periods are noted on the figure.

APPENDIX II: WATERSHED SLOPE ANALYSES

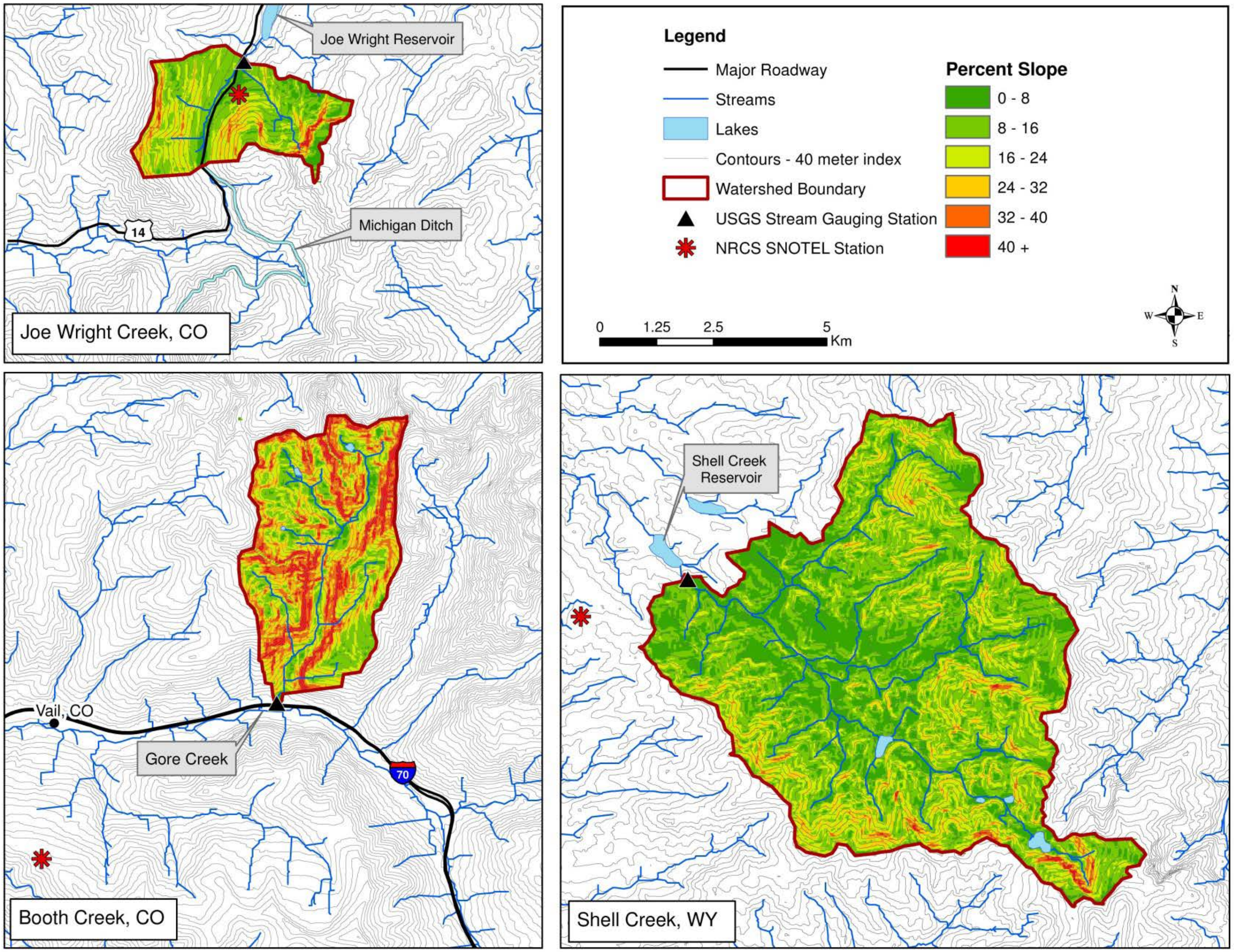

Figure A2.1: Slope map for the Joe Wright Creek, Booth Creek and Shell Creek Watersheds (Source: http://nationalmap.gov/viewer.html).

APPENDIX III: WATERSHED ASPECT ANALYSES

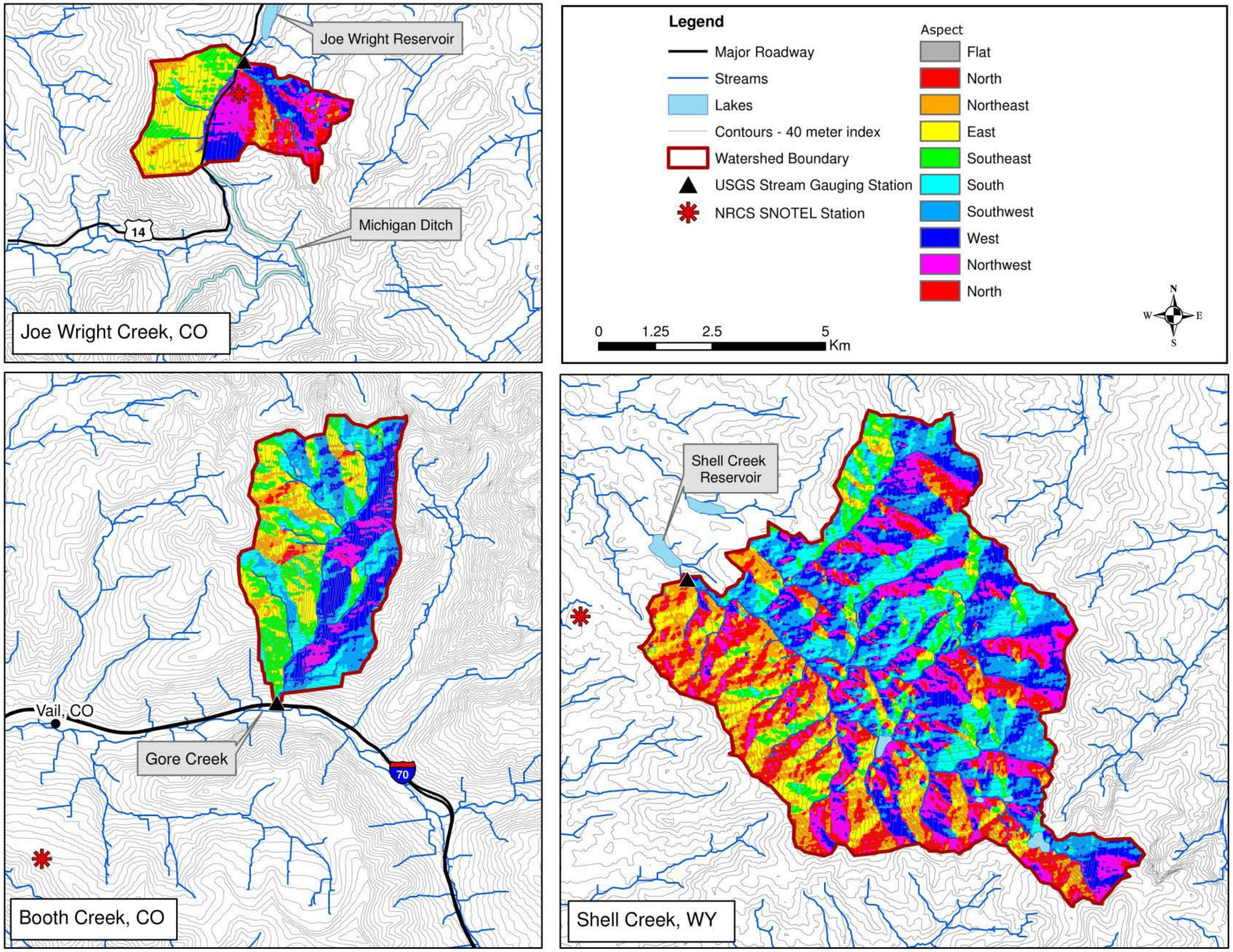

Figure A3.1: Aspect map for the Joe Wright Creek, Booth Creek and Shell Creek Watersheds (Source: http://nationalmap.gov/viewer.html).

APPENDIX IV: WATERSHED LAND COVER ANALYSES

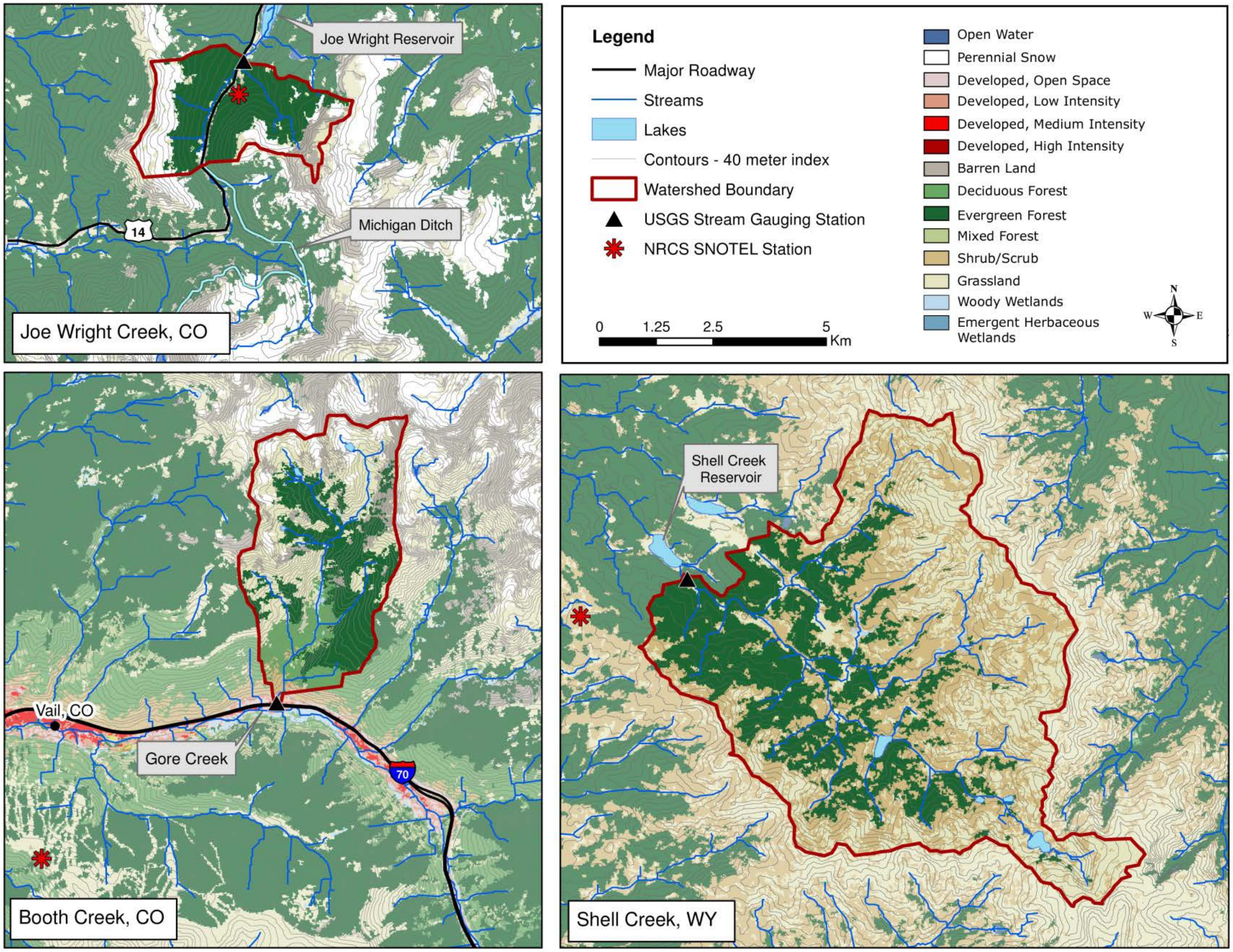

Figure A4.1: Land Cover map for the Joe Wright Creek, Booth Creek and Shell Creek Watersheds (Source: http://nationalmap.gov/viewer.html