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Evaluating Methods of Streamflow Timing to Approximate Snowmelt Contribution in High-Elevation Mountain Watersheds

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Abstract: Current streamflow timing metrics, such as the center of volume, or COV, use flow days, which are days at which a specific total streamflow volume, such as 50% for COV, has passed a given point. These metrics have been used as indicators for changes in the timings of snowmelt contributions to streamflow, but they may not be indicating changes to snowmelt timings as they have a fixed volume. Using manually extracted start and end days for high-elevation, mountainous watersheds, which are regarded as true values, we developed a new method to estimate when snowmelt is entering streams. Based on RMSE and NSE values, this new method is a better model for snowmelt-driven streamflow than using flow days or the COV. In general, the trend analysis results from the different timing metrics indicate an earlier timing in the year. This method was suitable for 40 different-sized watersheds in Colorado, USA; these are all snow-dominated watersheds in a semi-arid climate. This method could be used to assess watersheds in different climates, including those that are not as snow-dominated.

Keywords: streamflow; snowmelt; timing metrics

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1. Introduction

High-elevation, semi-arid, and arid regions that receive limited precipitation during the summer are dependent on snowmelt as a source of water. In Colorado, snowfall comprises more than 60% of the annual precipitation and accounts for more than 70% of runoffs [1,2], and the timing of the snowmelt in high-elevation watersheds is crucial for estimating water availability [3]. While the specifics of how climate change will affect the Colorado streams are inconclusive [4], due, in part, to the complexity of the snowmelt-dominated watersheds [5], research has suggested that the mountain snowpack will decrease [6], which will impact spring runoff and streamflow [7]. The center of volume (COV), also called center timing (CT), has been adopted as a common streamflow timing metric to help evaluate changes occurring within watersheds [4,8–14]. Similar flow dates, i.e., 20% and 80% of the annual volume, have also been used in combination with the COV as proxies for snowmelt timings [4], specifically the start (t_{Q20}) and end (t_{Q80}) of a snowmelt contribution to streamflow.

Past trend analyses using the COV method in the western United States have shown that the timing of the 50% flow has been occurring earlier [4,10,14]. However, these studies used percentages of the total flow as indicators for changes in the snowmelt timings, but this may not be an appropriate application of the COV method [15]. Large precipitation events can influence the day when the COV occurs and may yield results that are not representative of changes in the snowmelt timings [12,15]. Additionally, COV can be more strongly influenced by the inter-annual variability in streamflow volume than snowmelt timing [15]. When first introduced, the stated purposes of the COV method were to identify any changes in streamflow timings and even minimize "the effect of erratic winter flows" [16]. In [16], the following has been stated: "whether the half-flow date is the best criterion, or even a useful one, for use in analysis of streamflow timing can be determined only by further investigation. Proposals of alternative measures by other hydrologists will be welcome". While the use of the COV and other flow dates (e.g., 20% or 80%) is not inherently problematic, the specific application related to snowmelt timing must be evaluated [15], in part because these are static quantities. Our research seeks to address these concerns. Since winter snowpack and spring snowmelt comprise such crucial roles in the hydrologic cycle for high-elevation, snowmelt-dominated watersheds, this paper evaluates the COV and other fixed-flow dates and a new dynamic streamflow volume–date method to identify the timing of snowmelt-driven streamflow. Specifically, the objectives are as follows: (i) develop a new method with the use of a hydrograph to determine the "true" values of the start and end of snowmelt contributions to streamflow; (ii) assess the difference in using a new dynamic streamflow volume–date method versus the COV and other fixed-flow dates; (iii) compare results using a trend analysis on the snowmelt-driven streamflow timing.

2. Materials and Methods

We examined the streamflow timings for a 40-year period (1976 through 2015) in headwater streams, ranging in size from 4 to 878 km^2 and located at elevations greater than 2000 m above sea level across the Southern Rocky Mountains of Colorado. Streamflow data were obtained from the National Water Information System for 40 gauging stations monitored by the United States Geological Survey (USGS), with at least 25 years of records (Table A1).

We estimated the start and end of the snowmelt contribution to streamflow using the following four different methods: manual extraction (used as the "truth"); a dynamic volume cumulative hydrograph separation method (described in the following paragraph); fixed-flow days of 20%, 50%, and 80% of the total volume (t_{Q20}, t_{Q50} or COV, and t_{Q80}) [4]; a static-flow day of 50% of the streamflow from January to July (t_{Dudley}) [14].

Due to the majority of streamflow being driven by snowmelt, the start and end of the snowmelt contribution are relatively easy to identify. By performing a visual evaluation of the annual hydrograph using the daily time series of the streamflow data, we manually extracted the start and end of the snowmelt contribution to the streamflow three times for each station and year. These manually extracted values were used as the "truth" values to evaluate our dynamic volume cumulative hydrograph division method for snowmelt timings, with the flow days used in past studies [4,14]. The start of the snowmelt contribution was determined by the initial increase in streamflow, whereas the end of the snowmelt contribution was when the hydrograph started to return to baseflow. We manually extracted these days for all years at the following three stations, which are representative of size, elevation, and location: Black Gore Creek, Michigan River, and Crystal River (see Table A1).

From the daily time series, we created cumulative hydrographs for each station and year. The shapes of the cumulative annual hydrographs for high-elevation streams in Colorado are characterized by shallow slopes in the winter and early spring when streamflow is baseflow-dominated, followed by steep slopes when snowmelt enters streams, and then a return to shallow slopes in late summer and early fall after the summer convective events have ended (Figure 1). Using these features of the cumulative hydrograph, we used the initial increase in the slope as the start of the snowmelt contribution and the return to baseflow as the end of the snowmelt contribution. After converting the daily hydrograph into a cumulative hydrograph for each year, we calculated the cumulative average baseflow twice, at the beginning of the year (January through March) and end of the year (October through December) (Figure 1). The calendar year was used instead of the U.S. water year (1 October to 30 September) due to the large precipitation events that can occur as late as September and October, which can make estimating the average baseflow difficult [12,17]. We then compared the cumulative annual baseflow with the cumulative annual hydrograph to find the baseflow departure threshold, which is a large enough departure of the cumulative annual hydrograph from the baseflow to signal that snowmelt was the dominant contribution to streamflow. We used the manually extracted days to quantify the baseflow departure threshold for the start (t_{start}) and end (t_{end}) of the snowmelt contribution. We calculated a half-flow snowmelt contribution date (t_{se}) by finding the volume of water that has passed between our identified start and end dates to compare with the fixed-flow dates.

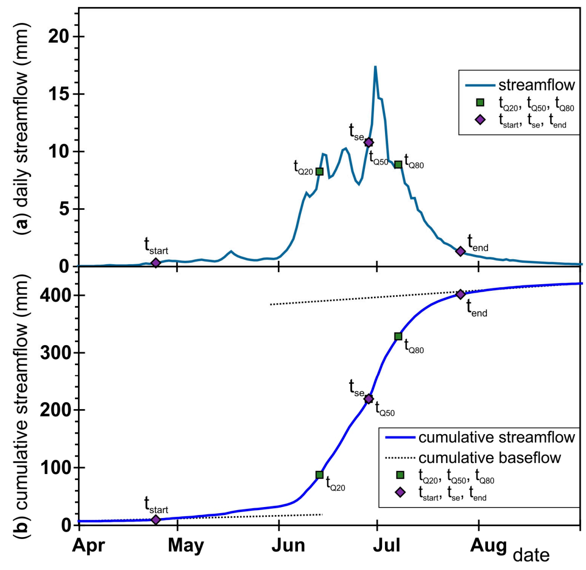

Figure 1. Example year of (**a**) streamflow data and (**b**) cumulative streamflow and cumulative baseflow illustrating the dates derived from the new method (t_{start}, t_{se}, and t_{end}) versus the COV and other fixed-flow dates (t_{Q20}, t_{Q50}, and t_{Q80}).

To determine when the slope of the cumulative hydrograph changes, we determined the baseflow departure thresholds that maximize the Nash–Sutcliffe efficiency (NSE) [18] and minimize the root-mean-square error (RMSE) values across the three different sample watersheds by trial and error and by comparison to the manually extracted dates. NSE values greater than 0.5 are typically considered satisfactory [19]. Baseflow departure thresholds were chosen for values that maximized the NSE and minimized the RMSE. The trends in the snowmelt-driven streamflow timings were calculated using the Mann–Kendall test [20,21] for significance and the Theil–Sen's slope [22,23] to quantify the rate of change.

3. Results

The optimal baseflow departure thresholds for identifying t_{start} and t_{end} were found to be 10 and 17.5 mm/day, respectively (Table 1). For both the start and end of the snowmelt contribution, the cumulative hydrograph separation method resulted in higher NSE values (>0.50) than when using the 20% and 80% flow days as proxies (<0). The RMSE values were lower for the cumulative hydrograph separation (5.42 to 8.00 days for t_{start} and t_{end}) than for the flow days (29 to 43 days for t_{Q20} and t_{Q80}) (Table 1). For the snowmelt contribution, the calculated t_{start} and t_{end} were consistent with the manually extracted days more often than when using t_{Q20} and t_{Q80} (Figure 2). For the beginning of the contribution, there is less variability with t_{start} than with t_{Q20}, and t_{start} is clustered more closely along the 1:1 line. The t_{Q20} tends to occur for about a week, and sometimes an entire month, later in the season than the manually extracted day and the day estimated using t_{start} (Figure 2a). For the end of the contribution, t_{Q80} is less variable than t_{Q20}, but, again, this method (t_{Q80}) results in the timing occurring one to two months later in the season than what is suggested from the manually extracted day and t_{end} (Figure 2c). Conversely, using the half-flow estimations, both t_{Dudley} and t_{Q50} occur around a week later than the manually extracted and t_{se} values (Figure 2b).

Table 1. Root-mean-square error (RMSE) and Nash–Sutcliffe efficiency (NSE) for each streamflow timing metric, as well as the baseflow factors used in developing the t_{start} and t_{end}.

	NSE			RMSE		
Timing Metric	**Black Gore Cr.**	**Michigan R.**	**Crystal R.**	**Black Gore Cr.**	**Michigan R.**	**Crystal R.**
t_{start}	0.59	0.60	0.60	5.85	7.79	5.42
t_{Q20}	−13.75	−4.73	−25.35	35.07	29.33	43.19
t_{end}	0.69	0.53	0.64	6.32	7.04	8.00
t_{Q80}	−13.25	−9.31	−5.87	42.54	33.01	34.94
t_{se}	0.99	1.00	0.99	0.76	0.69	0.87
t_{Q50}	−0.15	0.98	0.84	9.30	1.59	3.39
t_{Dudley}	0.15	0.35	−0.29	8.02	9.17	9.72

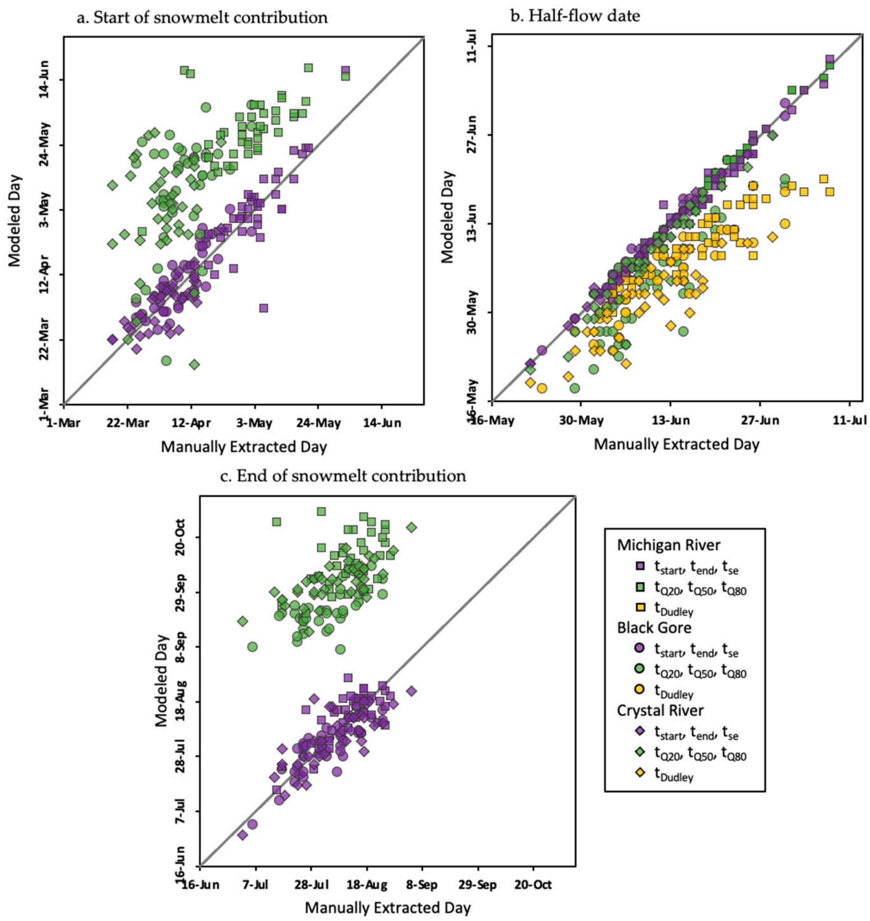

Figure 2. Comparison of the timing metrics for the (**a**) start, (**b**) half-flow, and (**c**) end of the snowmelt contribution to the streamflow.

At the start of the snowmelt contribution, the t_{start} trends ranged from 7.3 days/decade later to 4.2 days/decade earlier, with statistical significance ($p < 0.05$) at 15 out of the 40 stations. The t_{Q20} trends ranged from 8.8 days/decade later to 12.3 days/decade earlier, with statistical significance at three stations (Figure 3a). For the half-flow date, t_{se} ranged from 1.5 days/decade later to 4.5 days/decade earlier, with statistical significance at 11 stations. The t_{Q50} trends ranged from 4.5 days/decade later to 0.4 days/decade earlier, with statistical significance at six stations (Figure 3b). At the end of the snowmelt contribution, the t_{end} trends ranged from 8.7 days/decade later to 6.5 days/decade earlier, with statistical significance at nine stations. The t_{Q80} trends ranged from 5 days/decade later to 4 days/decade earlier, with statistical significance at five stations (Figure 3c). The t_{Dudley} ranged from 5.8 days/decade later to 1.8 days/decade earlier, with statistical significance at 11 stations (Figure 3d).

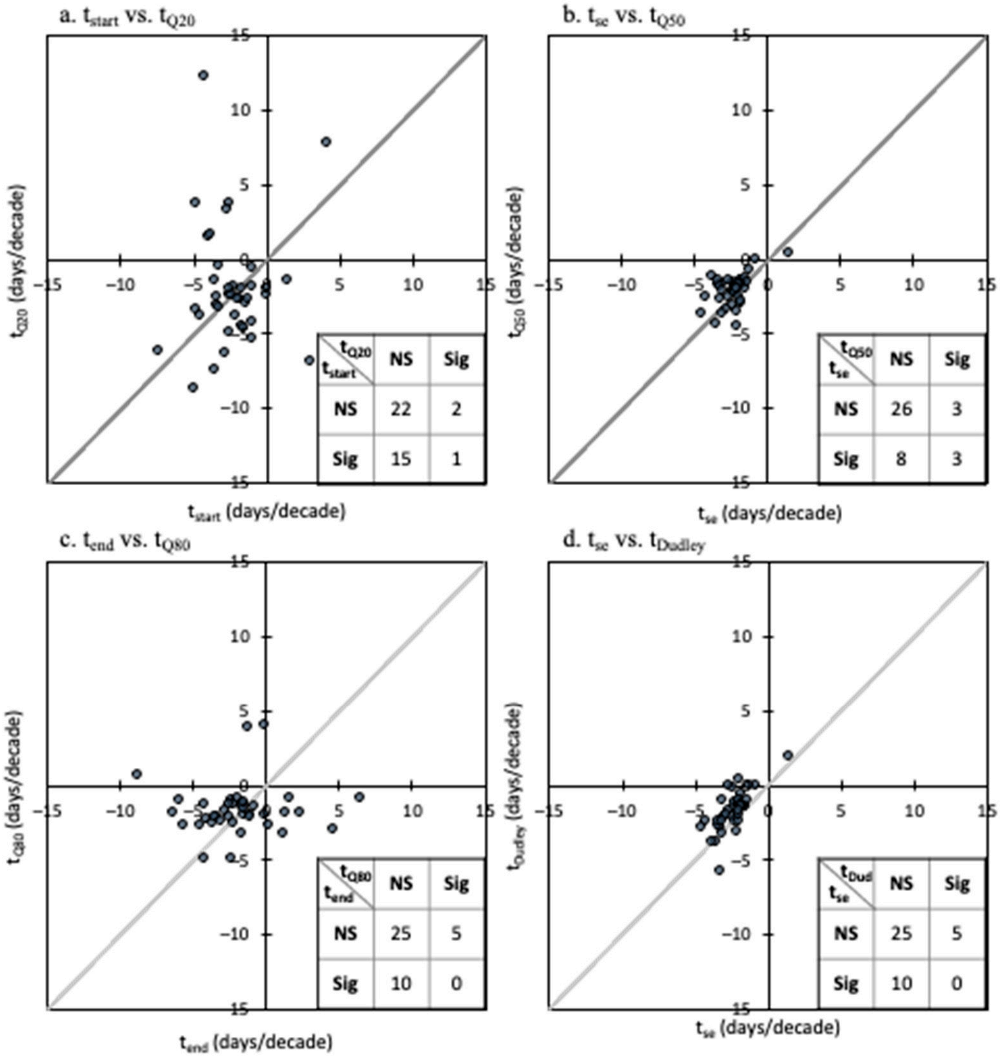

Figure 3. Comparison of the timing metric trends for the (**a**) start, (**b**) half-flow, and (**c**) end of the snowmelt contribution to the streamflow, and (**d**) Dudley. The tables in the bottom right corner indicate the number of stations at which the trends were not significant (NS) and significant (Sig).

4. Discussion

4.1. Method Evaluation

Based on the NSE and RMSE values of the two methods, the cumulative hydrograph separation method is an improvement over using flow days as proxies for the start and end of snowmelt contributions (Table 1). The mean values would be a better estimator than using t_{Q20} and t_{Q80} as per the NSE values, whereas the proposed method reasonably estimates the t_{start} and t_{end}. The poor performance of t_{Q20} and t_{Q80} as a model for the start and end of snowmelt contributions could be a response to other variables, such as changes in the total annual discharge, which did not have statistically significant trends in this study, instead of changes to the snowmelt streamflow [15]. This method evaluation was conducted for 3 out of 40 watersheds, which were representative in size, elevation, and location of the basins in the study. A baseflow departure threshold was optimized to identify the snowmelt streamflow timings for three basins of disparate characteristics (10 and 17.5 mm/day for the start and end). These values may need to be altered when applied to other regions, especially with different climates. This may be relevant for watersheds that are less snowmelt-dominated. The basins assessed herein are in Colorado, and more than 70% of the annual runoff comes from snowmelt [1,2]. Further, subsequent analyses should examine the timing between snowmelt across a basin and when this melted water appears in a stream, but this is complex and a function of the spatiotemporal variability in accumulation, energy balance, and melt [24].

4.2. Trends in Streamflow Timing Metrics

The calculated trends demonstrate the differences in sign, magnitude, and statistical significance between the two methods. In general, for the start of snowmelt, the two methods show that snowmelt timing is occurring earlier in the year, but the magnitudes of the trends for t_{Q20} are larger than those for t_{start}. The results from the different timing metrics show that the flow days are occurring earlier and are consistent in magnitude. For the end of snowmelt, the trends for both methods show that the end of the snowmelt contribution is occurring earlier in the year, although the trends for t_{end} were larger in magnitude than those for t_{Q80}. With the exception of the calculated trends for t_{Dudley}, the proposed method had greater statistical significance than when using t_{Q20}, t_{Q50}, and t_{Q80}. Based on the method evaluation results, the trend analyses conducted using the flow dates should be viewed with greater caution when making statements about changes in the timing of snowmelt.

Clow [4] used the Regional Kendall test for trend analyses and snowmelt timing and found no trends that occurred later in the year. All of the results indicated that the various timing metrics shifted earlier in the year. Statistical significance was observed for 43%, 62%, and 36% of the stations for t_{Q20}, t_{Q50}, and t_{Q80} [4]. The magnitudes of the timing metrics were similar to the findings in this study. The differences in the results can be partially explained by our use of the Mann–Kendall test instead of the Regional Kendall test; using the Regional Kendall test can produce trends that are smaller in magnitude than observed trends at individual sites [25]. The station selection criteria also differed from a 29-year record ending in 2007 [4] to a 40-year record, with the different lengths of record producing different results [26]. Using the half-flow date for the winter–spring streamflow, Dudley et al. [14] calculated the trends in streamflow timing from snowmelt across the United States. They used one station in Colorado for the period from 1960 to 2014. Their timing variable occurred 5 to 10 days earlier with no statistical significance; locations nearest to Colorado, in Wyoming and New Mexico, illustrated similar results. Only 3 stations out of 56 indicated their variable occurring later in the year [14].

Stewart et al. [11] examined the streamflow trends in the western United States and Canada from 1948 to 2002. They used the COV method in combination with an algorithm that determined the onset of snowmelt contributions [27], which is similar to the method developed here. For Colorado, they observed a few statistically significant trends in the COV, which correlated with our findings. However, for the onset of melt, they observed statistical significance at only 1 out of 15 stations, whereas we found statistical significance at 15 out of 40 stations. Their trends were also larger in magnitude, ranging from 20 days/decade earlier to 20 days/decade later, but the majority of stations were only 5 days/decade earlier, which is similar to the presented results (Figure 3). The shorter study length and the timing of the study period could explain these differences [26], as well as the specific period of record [28]. Additionally, we used stations at higher elevations than Stewart et al. [11], so perhaps there is greater statistical significance occurring at these higher elevation gauging stations, in part because snowmelt is occurring earlier at higher elevations in Colorado [4,29].

These different results indicate that changes are occurring in the streamflow timings for mountain streams and highlight the importance of using a method that is representative of the occurring physical processes. Additional methods to estimate snowmelt-driven streamflows exist (e.g., isotopic analyses), but they have greater costs and limit the spatial and temporal coverage compared with the network of gauging stations across the western, mountainous United States. Using and further refining the appropriate snowmelt-driven streamflow metrics is important for water forecasters and managers making decisions about water storage and reservoirs for the future [30,31].

5. Conclusions

The COV and other streamflow dates have become popular streamflow timing metrics to examine snowmelt timings in streams. These metrics do not consistently identify when the represented processes are occurring. To address these shortcomings, we used Colorado streamflow data and developed a new method to represent snowmelt-driven streamflow timings and identify trends related to these timing variables. We show that the COV and flow days are not robust metrics for estimating snowmelt timings. From evaluation statistics (NSE and RMSE), our proposed method performed well at modeling the start and end of snowmelt contributions to streamflow. More stations had statistically significant trends with the proposed method compared to other streamflow metrics from similar analyses. The method presented herein should be tested, verified, and modified as needed in areas where the transition from a baseflow- to a snowmelt-dominated hydrograph is not as apparent. Additionally, our findings demonstrate the need to continue to evaluate and adapt the current methods used for evaluating snowmelt-driven streamflow timings.

Author Contributions: Conceptualization, A.K.D.P. and S.R.F.; methodology, A.K.D.P. and S.R.F.; software, A.K.D.P.; validation, A.K.D.P.; formal analysis, A.K.D.P.; investigation, A.K.D.P.; resources, S.R.F.; writing—original draft preparation, A.K.D.P. and S.R.F.; writing—review and editing, A.K.D.P. and S.R.F.; visualization, A.K.D.P.; supervision, S.R.F.; funding acquisition, S.R.F. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data used in this paper are available online from the U.S. Geological Survey National Water Dashboard <https://dashboard.waterdata.usgs.gov/> (last accessed on 2 March 2023).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Overview of Watersheds Analyzed

The appendix provides a map (Figure A1) of the watersheds used in the assessment of the new method proposed in this paper and their metadata (Table A1).

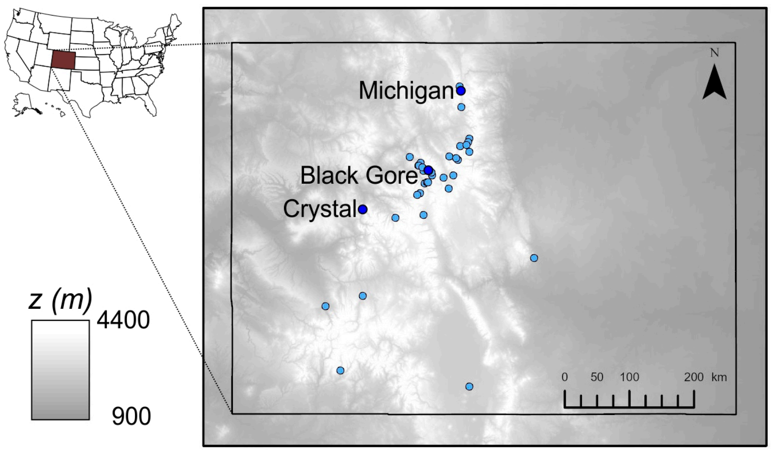

Figure A1. A site map illustrating the state of Colorado within the USA and an elevation map of Colorado with the 40 study watersheds and the three focus watersheds (Black Gore Creek, Crystal River, and Michigan River).

Table A1. Summary of the watersheds used in the assessment of the new method. This includes the following: U.S. Geological Survey station number, area, outlet elevation, and outlet location (latitude and longitude). The watersheds examined in detail are denoted with an asterisk (*).

Watershed Name	HUC	Latitude (°N)	Longitude (°W)	Elevation (m)	Area (km^2)
Bighorn Creek	09066100	39.63999	−106.293	2629	12
Black Gore Creek *	09066000	39.59637	−106.265	2789	32
Blue River	09046600	39.45582	−106.032	2749	319
Bobtail Creek	09034900	39.76026	−105.906	3179	15
Booth Creek	09066200	39.64832	−106.323	2537	16
Cabin Creek	09032100	39.98582	−105.745	2914	13
Colorado River	09010500	40.32582	−105.857	2667	165
Conejos River	08245000	37.30029	−105.747	3007	104
Crystal River *	09081600	39.23264	−107.228	2105	433
Darling Creek	09035800	39.79719	−106.026	2725	23
Dickson Creek	09058610	39.70411	−106.457	2818	9
Eagle River	09063000	39.50832	−106.367	2638	182
East Meadow Creek	09058800	39.73165	−106.427	2882	9
Fraser River	09022000	39.84582	−105.752	2902	27
Freeman Creek	09058700	39.69832	−106.446	2845	8
Gore Creek	09065500	39.62582	−106.278	2621	38
Halfmoon Creek	07083000	39.17221	−106.389	2996	61
Homestake Creek	09064000	39.40554	−106.433	2804	92
Joe Wright Creek	06746095	40.53998	−105.883	3045	8
Keystone Gulch	09047700	39.59443	−105.973	2850	24
Lake Fork	09124500	38.29888	−107.23	2386	878
Michigan River *	06614800	40.49609	−105.865	3167	4
Middle Creek	09066300	39.64582	−106.382	2499	15
Missouri Creek	09063900	39.39026	−106.47	3042	17
Piney River	09059500	39.79572	−106.574	2217	219
Pitkin Creek	09066150	39.6436	−106.303	2598	14
Ranch Creek	09032000	39.94999	−105.766	2640	52
Red Sandstone Creek	09066400	39.68276	−106.401	2808	19
Roaring Fork River	09073300	39.1411	−106.774	2475	196
Rock Creek	07105945	38.70749	−104.847	2000	18
S Fork of Williams	09035900	39.80054	−106.026	2728	71
St. Louis Creek	09026500	39.90999	−105.878	2737	85
Tenmile Creek	09050100	39.57526	−106.111	2774	239
Turkey Creek	09063400	39.5226	−106.337	2718	61
Uncompahgre River	09146200	38.18388	−107.746	2096	386
Vallecito Creek	09352900	37.4775	−107.544	2410	188
Vasquez Creek	09025000	39.92026	−105.785	2673	72
Wearyman Creek	09063200	39.52221	−106.324	2829	25
Williams Fork	09035500	39.77888	−105.928	2987	42

References

1. Serreze, M.C.; Clark, M.P.; Armstrong, R.L.; Mcginnis, A.; Pulwarty, R.S. Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data. *Water Resour. Res.* **1999**, *35*, 2145–2160. [CrossRef]
2. Li, D.; Wrzesien, M.L.; Durand, M.; Adam, J.; Lettenmaier, D.P. How much runoff originates as snow in the western United States, and how will that change in the future? *Geophys. Res. Lett.* **2017**, *44*, 6163–6172. [CrossRef]
3. Schlaepfer, D.R.; Lauenroth, W.K.; Bradford, J.B. Consequences of declining snow accumulation for water balance of mid-latitude dry regions. *Glob. Chang. Biol.* **2012**, *18*, 1988–1997. [CrossRef]
4. Clow, D.W. Changes in the Timing of Snowmelt and Streamflow in Colorado: A Response to Recent Warming. *J. Clim.* **2010**, *23*, 2293–2306. [CrossRef]
5. Bales, R.C.; Molotch, N.P.; Painter, T.H.; Dettinger, M.D.; Rice, R.; Dozier, J. Mountain hydrology of the western United States. *Water Resour. Res.* **2006**, *42*, W08432. [CrossRef]
6. Stewart, I.T. Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrol. Process.* **2009**, *23*, 78–94. [CrossRef]
7. Leung, L.R.; Qian, Y.; Bian, X.; Washington, W.M.; Han, J.; Roads, J.O. Mid-Century Ensemble Regional Climate Change Scenarios for the Western United States. *Clim. Chang.* **2005**, *62*, 75–113. [CrossRef]

8. Johnson, F.A. Comments on Paper by Arnold Court, "Measures of Streamflow Timing". *J. Geophys. Res.* **1964**, *69*, 3525–3527. [CrossRef]
9. Satterlund, D.R.; Eschner, A.R. Land Use, Snow, and Streamflow Regimen in Central New York. *Water Resour. Res.* **1965**, *1*, 397–405. [CrossRef]
10. Stewart, I.T.; Cayan, D.R.; Dettinger, M.D. Changes in Snowmelt Runoff Timing in Western North America under a "Business as Usual" Climate Change Scenario. *Clim. Chang.* **2004**, *62*, 217–232. [CrossRef]
11. Stewart, I.T.; Cayan, D.R.; Dettinger, M.D. Changes toward Earlier Streamflow Timing across Western North America. *J. Clim.* **2005**, *18*, 1136–1155. [CrossRef]
12. Fassnacht, S.R. Upper versus lower Colorado River sub-basin streamflow: Characteristics, runoff estimation and model simulation. *Hydrol. Process.* **2006**, *20*, 2187–2205. [CrossRef]
13. Rauscher, S.A.; Pal, J.S.; Diffenbaugh, N.S.; Benedetti, M.M. Future changes in snowmelt-driven runoff timing over the western US. *Geophys. Res. Lett.* **2008**, *35*, L16703. [CrossRef]
14. Dudley, R.W.; Hodgkins, G.A.; McHale, M.R.; Kolian, M.J.; Renard, B. Trends in snowmelt-related streamflow timing in the conterminous United States. *J. Hydrol.* **2017**, *547*, 208–221. [CrossRef]
15. Whitfield, P.H. Is 'Centre of Volume' a robust indicator of changes in snowmelt timing? *Hydrol. Process.* **2013**, *27*, 2691–2698. [CrossRef]
16. Court, A. Measures of Streamflow Timing. *J. Geophys. Res.* **1962**, *67*, 4335–4339. [CrossRef]
17. Kampf, S.K.; Lefsky, M.A. Transition of dominant peak flow source from snowmelt to rainfall along the Colorado Front Range: Historical patterns, trends, and lessons from the 2013 Colorado Front Range floods. *Water Resour. Res.* **2015**, *52*, 407–422. [CrossRef]
18. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models Part I—A discussion of principless. *J. Hydrol.* **1970**, *10*, 282–290. [CrossRef]
19. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Trans. ASABE* **2007**, *50*, 885–900. [CrossRef]
20. Mann, H.B. Nonparametric Tests Against Trends. *Econometrica* **1945**, *13*, 245–259. [CrossRef]
21. Kendall, M.; Gibbons, J.D. *Rank Correlation Methods*, 5th ed.; Edward Arnold: London, UK, 1990.
22. Theil, H. A rank-invariant method of linear and polynomial regression analysis. *Proc. R. Neth. Acad. Sci.* **1950**, *53*, 386–392.
23. Sen, P.K. Estimates of the Regression Coefficient Based on Kendall's Tau. *Am. Stat. Assoc. J.* **1968**, *63*, 1379–1389. [CrossRef]
24. Fassnacht, S.R. A Call for More Snow Sampling. *Geosciences* **2021**, *11*, 435. [CrossRef]
25. Fassnacht, S.R.; Cherry, M.L.; Venable, N.B.H.; Saavedra, F. Snow and albedo climate change impacts across the United States. *Cryosphere* **2016**, *10*, 329–339. [CrossRef]
26. Venable, N.B.H.; Fassnacht, S.R.; Adyabadam, G.; Tumenjargal, S.; Fernandez-Gimenez, M.; Batbuyan, B. Does the length of station record influence the warming trend that is perceived by Mongolian herders near the Khangai Mountains? *Pirineos* **2012**, *167*, 69–86. [CrossRef]
27. Cayan, D.R.; Kammerdiener, S.A.; Dettinger, M.D.; Caprio, J.M.; Peterson, D.H. Changes in the Onset of Spring in the Western United States. *Bull. Am. Meteorol. Soc.* **2001**, *82*, 399–415. [CrossRef]
28. Fassnacht, S.R.; Hulstrand, M. Snowpack variability and trends at long-term stations in northern Colorado, USA. *Proc. IAHS* **2015**, *371*, 131–136. [CrossRef]
29. Fassnacht, S.R.; Venable, N.B.H.; McGrath, D.; Patterson, G.G. Sub-Seasonal Snowpack Trends in the Rocky Mountain National Park Area, Colorado, USA. *Water* **2018**, *10*, 562. [CrossRef]
30. Gomez-Landesa, E.; Rango, A. Operational snowmelt runoff forecasting in the Spanish Pyrenees using the snowmelt runoff model. *Hydrol. Process.* **2002**, *16*, 1583–1591. [CrossRef]
31. Bryan, Z. *Something in Orange*; Warner Records Inc.: Los Angeles, CA, USA, 2022.