Supplemental Information

Rainfall-Runoff Event Detection and Identification (RREDI) Toolkit

The RREDI toolkit was developed to automatically separate rainfall-runoff events for any watershed using time-series signal processing in four steps (Figure S1) (Canham & Lane, 2022). First, rainfall-runoff event pairs are identified using daily streamflow and precipitation data (step 1) and event start, peak, and end timing are identified using 15-minute streamflow data (step 2). Then, rainfall-runoff event metrics are calculated (step 3) and finally event flagging is performed to remove incorrectly identified events (step 4). The RREDI toolkit was fully automated using the open-source python language.

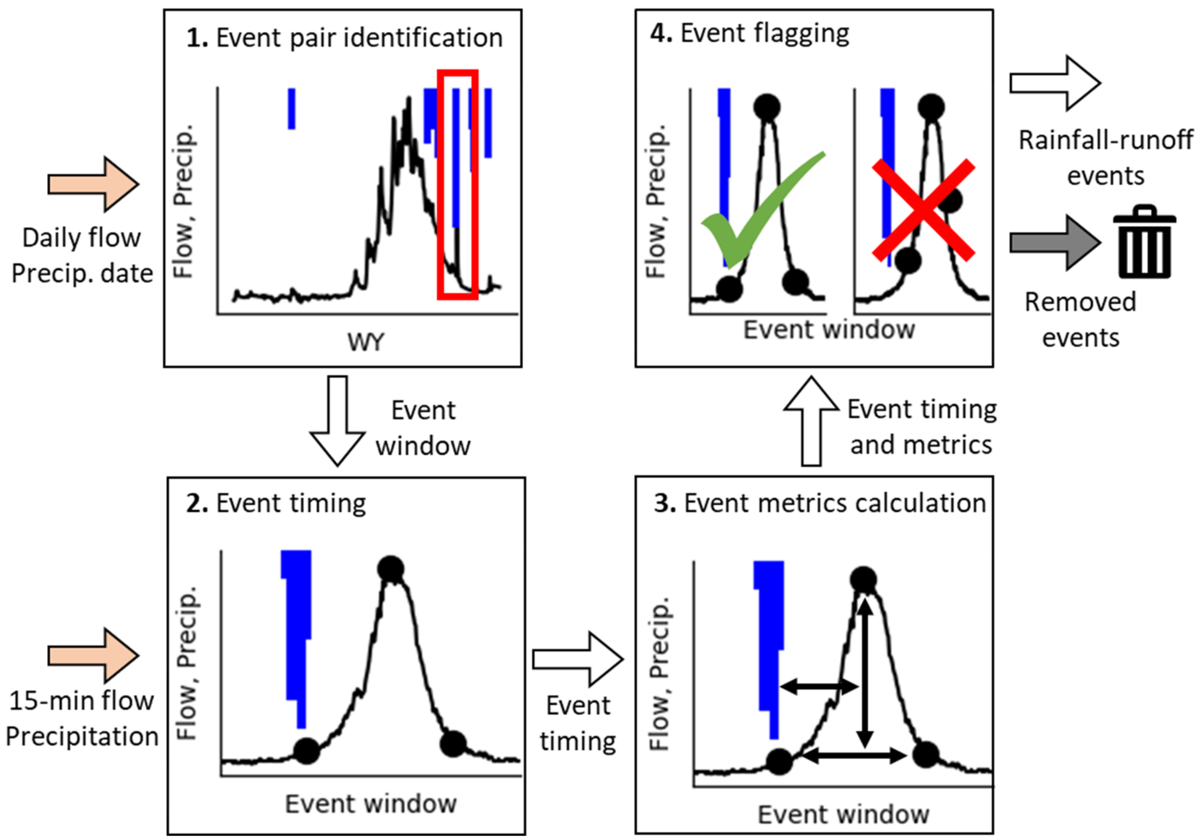

Figure S1: The four key steps for the RREDI toolkit: Step 1. Event pair identification, Step 2. Event timing, Step 3. Event metrics calculation, and Step 4. Event Flagging. Data inputs are shown as orange arrows, removed events are grey arrows, and outputs are white arrows.

Data inputs

Streamflow (daily and 15-minute) and precipitation (sub-daily) data are required inputs to the RREDI toolkit for each study watershed. In this study, streamflow data was obtained from USGS NWIS and hourly precipitation timeseries was obtained for the watershed centroid from the Analysis of Record Calibration (AORC) 4km^2 resolution dataset for water years 1980 to 2022 (National Weather Service Office of Water Prediction, 2021). Linear interpolation was then used to spread the hourly rainfall over the timestep at the AORC resolution of 1 mm.

Step 1: Event pair identification

Rainfall-runoff event pairs were identified based on the co-occurrence of separately identified rainfall and runoff events from the overlapping period of record (Figure S1, Step 1). Individual rainfall events were identified from the interpolated AORC-based precipitation timeseries over the period of record using a watershed-specific storm event gap. First, storm events were generated using the interpolated precipitation timeseries and a series of potential storm gaps ranging from 0.5 to 24 hours in half hour increments. A curve was then created of the number of storms generated based on each potential storm gap (Figure S2). The precipitation gap was identified as the increment at which the 2nd derivative of the curve decreased below zero. The identified gaps ranged from 4.5 hours for Clear Creek, Arroyo Seco, and Cache La Poudre watersheds to 9 hours for Shitike Creek (Table S1). For each storm, the storm duration, cumulative and total depth, storm intensity, and 60-minute intensity were calculated.

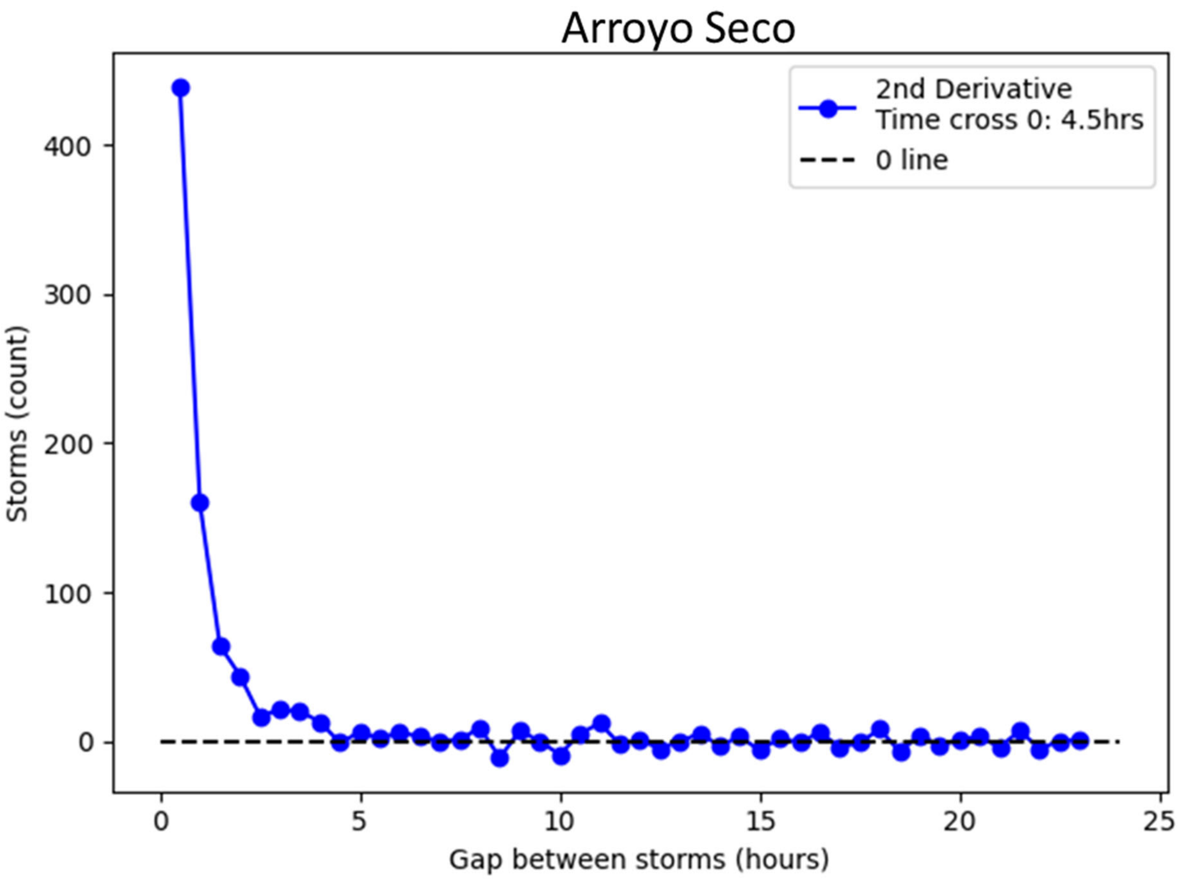

Figure S2: Storm gap identification method. Example from Arroyo Seco. Where the 2nd derivative of the number of storms generated for each of the identified gaps between 0.5 to 24 hours on the half hour is shown (blue). In this example, the identified storm gap is 4.5 hours.

Table S1: RREDI toolkit watershed specific parameters

Watershed	Storm gap (hr)	Stream Classification*
Arroyo Seco	4.5	8
Ash Canyon Creek	5.5	2
Cache La Poudre River	4.5	3
Camp Creek	6	3
Clear Creek	4.5	3
Shitike Creek	9	3
Thompson River	7	2
Valley Creek	4.5	3
Wet Bottom Creek	7	7

*Stream classification is divided into nine natural hydrologic classes (Lane et al., 2018) used in streamflow signal processing (Patterson et al., 2020).

To identify runoff events, automated feature detection and signal processing of daily average streamflow data was applied following Patterson et al. (2020). Signal processing theory provided techniques including data smoothing, peak detection, and window processing that were used to automate detection of features from a timeseries. Runoff event features were identified by fitting a gaussian filter and windowing daily streamflow time series. Sign changes in the derivative of a spline curve fit to the filtered streamflow data within each window were used to identify runoff event peaks. The start and end date of the runoff event was then identified using a combination of the relative magnitude and slope of the gaussian filter within the window (Patterson et al., 2020). The parameters for the spline curve and gaussian filter, used across all study watersheds, were manually tuned to identify runoff peaks (Table S2). Finally, to identify rainfall-runoff event pairs, for each rainfall event an associated runoff event was searched for from the rainfall date through the following day. If a runoff event was found within the search window, a rainfall-runoff event pair was returned. If multiple runoff events were associated with a rainfall event, multiple pairs were returned. If no runoff event was found, no event pair was returned. For each event pair, the event window from the start of rainfall to the end of runoff was passed to step 2.

Table S2: RREDI toolkit calibrated parameters and thresholds

Parameter	Value
Fall flush gaussian filter sigma (Patterson et al., 2020) (step 1)	0.05
Fall flush gaussian filter broad sigma (Patterson et al., 2020) (step 1)	15
Fall flush peak sensitivity (Patterson et al., 2020) (step 1)	0.05
Start threshold (step 2)	0.1
End winter threshold (step 2)	0.25
End melt threshold (step 2)	0.75
End summer threshold (step 2)	0.25
End change rate (step 2)	0 to -0.05

Step 2: Event timing

For each rainfall-runoff event pair, the start, peak, and end times of each runoff event were identified (Figure S3 a) using the 15-minute streamflow and storm 60-minute intensity (Figure S1, Step 2). To identify the runoff event peak time, two search windows were used: the during-storm search window between the storm start time plus 15 minutes and the storm end time, and the after-storm search window between the storm end time and the storm end plus 24 hours. The first 12-hour local maximum extreme value and absolute maximum values were identified in each window. Three sequential comparisons were then completed to identify the runoff peak: (1) the peak was the after-storm local 12-hour maximum if it was greater than the during-storm absolute maximum, (2) the peak was the during-storm absolute maximum if it was greater than the after-storm absolute maximum, and (3) the peak was the greater of the after-storm absolute maximum and the during-storm 12-hour extreme maximum. The search window for the runoff start time was between the storm start time plus 15 minutes and the runoff peak time. The runoff start time was when the first derivative of the hourly streamflow timeseries exceeded a threshold of 0.1. If no value exceeded the threshold, the start of the search window was assigned as the storm start time. The search window for the runoff end time was between the peak time and the storm end plus 24 hours. The end time was set as the first time the hourly streamflow fell below the peak magnitude minus the start magnitude hydrologic season specific threshold (Table S2) and the next occurrence of either a local minimum or when the streamflow first derivative was between 0 and -0.05 and remained negative for the next 5 timesteps. Hourly streamflow was used for the start and end to decrease the noise inherent in the 15-minute streamflow data. All threshold values for event timing identification were determined based on the observation of many events across the nine study watersheds.

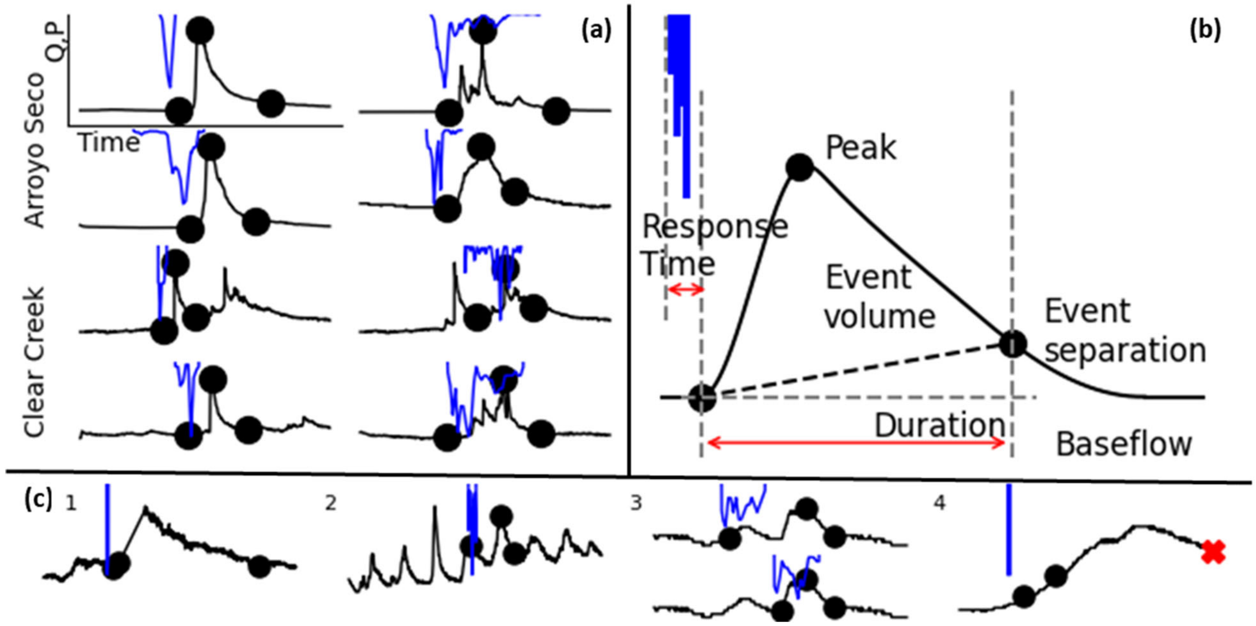

Figure S3: RREDI toolkit rainfall-runoff event examples and metrics. (a) Eight example rainfall-runoff events identified using the RREDI toolkit. Shown are the rainfall event (blue), the paired runoff event hydrograph (black), and the identified runoff start, peak, and end times and magnitudes (black dots). (b) Example rainfall-runoff event showing relevant rainfall-runoff event metrics including rise, peak, event volume, duration, and response time. Event separation (black dashed) between event flow volume and baseflow is shown. (c) Example events with issues flagged for removal (Step 4) including (1) missing 15-minute streamflow data, (2) diurnal cycling, (3) duplicate events where the top event has the same peak and end time as the bottom event, and (4) no end time found where the defaulted end is marked by a red x.

After the runoff event start, peak, and end times were identified, baseflow was separated from event flow to calculate event volume. Several digital filter baseflow separation methods were evaluated (Chapman & Maxwell, 1996; Eckhardt, 2005, 2008), but no identified method could accurately perform baseflow separation at the 15-minute resolution. Instead, linear interpolation between the streamflow magnitudes at the runoff event start and end was applied, resulting in a baseflow separation that closely followed what one would separate manually by visual inspection. For each rainfall-runoff event the start, peak, and end times and magnitudes and the event volume were passed as input to step 3.

Step 3: Event metrics calculation

For each rainfall-runoff event a set of 17 event metrics (Figure S4, Table S3) were calculated using the runoff event start, peak, and end timing and magnitudes and event volume (Figure S1, Step 3). Metrics fell within four runoff metric groups: runoff volume metrics, runoff magnitude metrics, runoff duration metrics, and rainfall-runoff timing metrics. Metrics utilized further in this study included those as follows (Figure S3 b). The runoff volume metric group included event volume. The runoff magnitude metric group included runoff peak as the peak magnitude. The runoff duration metric group included event duration calculated as the difference between the runoff event start and end times. The rainfall-runoff timing metric group included response time calculated as the difference between the storm start time and the runoff start time. Metrics were also normalized by contributing area to facilitate comparison between study watersheds. The event timing and calculated metrics for each rainfall-runoff event were then passed to step 4.

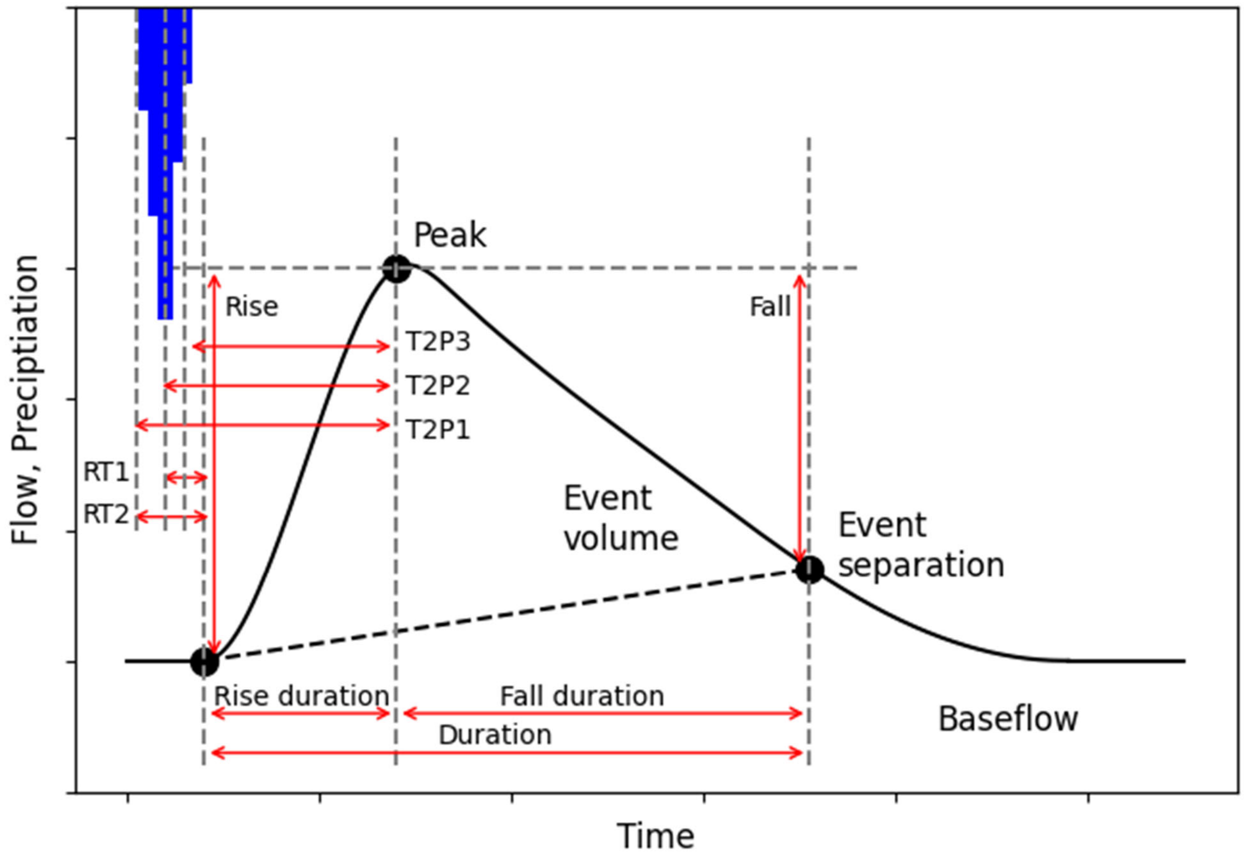

Figure S4: Calculated rainfall-runoff event metrics. Shown is an example rainfall-runoff event with the example hyetograph (blue) and hydrograph (black). The identified runoff start, peak, and end timing are shown consecutively (black dots). Event separation (black dashed) between event flow and baseflow is shown. Event metrics are defined by red arrows and listed in Table S3.

Table S3: RREDI toolkit rainfall-runoff metrics organized by event metric groups. Metric groups include runoff volume metric group, runoff magnitude metric group, runoff duration metric group, and rainfall-runoff timing metric group.

Runoff volume	Runoff magnitude	Runoff duration	Rainfall-runoff timing
Volume	Peak	Duration	Response time v1 (RT1)
Runoff ratio (RR)	Rise	Rise duration (rising_dur)	Response time v2 (RT2)
	Fall	Fall duration (falling_dur)	Time to peak v1 (T2P1)
	Rise (%) (Rise_percent)		Time to peak v2 (T2P2)
	Fall (%) (Fall_percent)		Time to peak v3 (T2P3)
	Rise rate (RiseRate)		
	Fall rate (FallRate)		

Set of equations included within the RREDI toolkit code.

Step 4: Event flagging

Four event identification issues were systematically flagged for removal: gaps in 15-minute streamflow data, diurnal cycling, duplicate events, and no identified event end time (Figure S1, Step 4). Since streamflow data gaps can cause error in event timing identification, events containing any 15-minute data gaps were removed from subsequent analysis (Figure S3 c 1). Diurnal flow cycling may be caused by snowmelt or water withdrawals (e.g., irrigation diversions) (Figure S3 c 2). To remove events influenced by diurnal flow cycling, we: (1) determined if an event fell within a diurnal cycling period and, if so, (2) determined if the event was influenced by the diurnal cycling (Figure S5). A diurnal cycling period was defined as when more than 50% of the daily range (daily maximum minus daily minimum) magnitudes of the four days before and after the event occurred within 20% of the mean daily range magnitude. An event was considered influenced by diurnal cycling if the event rise was less than three times the mean daily rise. This method was calibrated through visual inspection of many snowmelt- and irrigation-driven events across the study watersheds. Events were considered duplicates if the same runoff peak was identified for multiple storm events, such as occurred if the first storm generated no distinct runoff response (Figure S3 c 3). In this case, the rainfall-runoff event pair with the earlier rainfall event was removed. Finally, events were removed if no runoff end time was identified that met the established criteria (Figure S3 c 4). The retained rainfall-runoff events were then output as a rainfall-runoff even dataset.

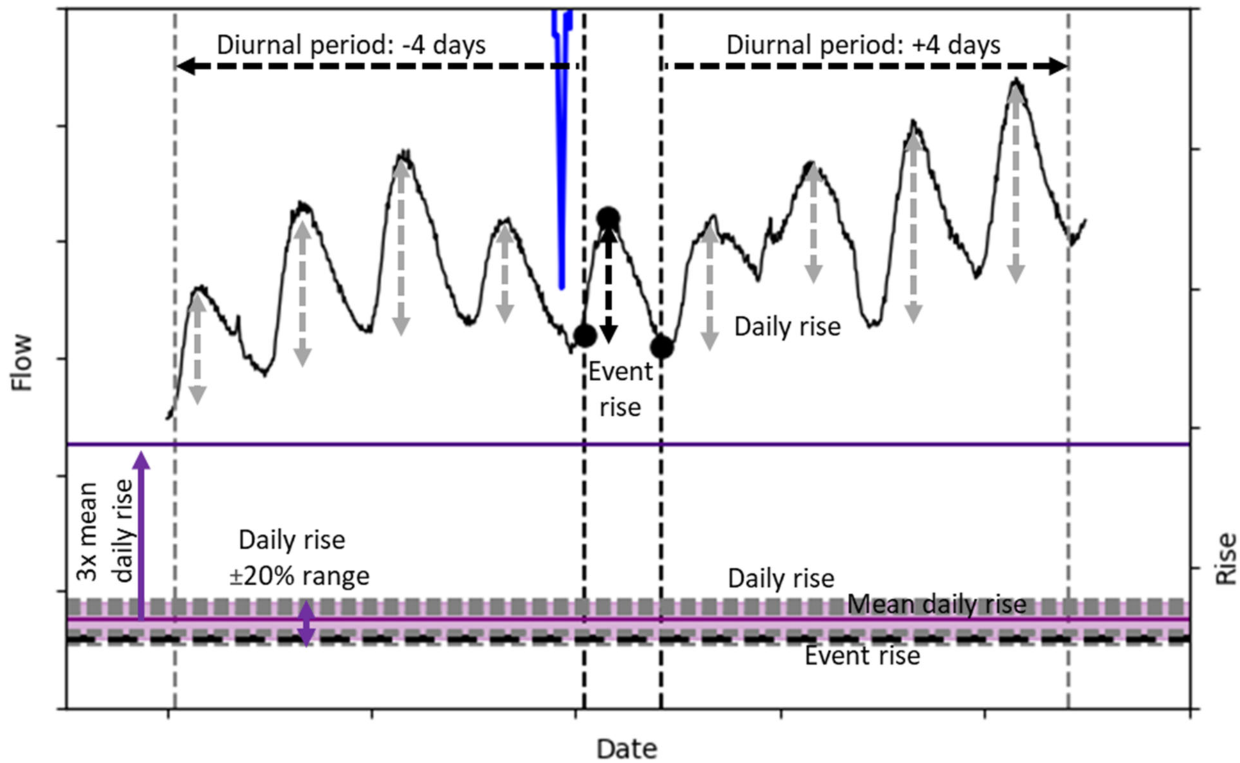

Figure S5: Diurnal cycling flagging method. Shown is an example hydrograph (black), a rainfall event (blue), and paired runoff event start, peak, and end points respectively (black dots). The diurnal cycling period is four days before and after the event start and end (vertical dashed grey). The rainfall-runoff event daily range magnitude (black dashed arrow) and the surrounding eight daily ranges (grey dashed arrow) are shown. The magnitude of the event range (black dashed horizontal), eight daily ranges (grey dashed horizontal), and mean of the daily ranges (purple) are shown. The ±20% of the mean daily range for determination of within a diurnal cycling period is shown (light purple). The threshold for determination if a rainfall-runoff event is influenced by diurnal cycling is three times the mean daily rise (dark purple). For this example, rainfall-runoff event, it was a diurnal cycling period, and the rainfall-runoff event was influenced by the diurnal cycling.

Table S4: Rainfall-runoff event timing and magnitudes. Including storm start, peak 60-minute intensity, and end times, storm peak 60-minute intensity, storm depth, antecedent precipitation depth, runoff start, peak, and end times and magnitudes, and event volume.

See excel files.

Table S5: RREDI toolkit rainfall-runoff performance results including event accuracy, flagging, and retention rates.

Watershed	Events pre-flagging (step 2) (#)	Events inspected (#)	Events inspected (%)	Events inspected with 15-minute flow data gaps (issue 1) (%)	Events inspected with diurnal cycling (issue 2) (%)	Events inspected with duplicate events (issue 3) (%)	Events inspected with no end (issue 4) (%)	Event accuracy pre-flagging (step 2) (%)	Events accuracy post-flagging (step 4) (%)	Events retained post-flagging (step 4) (#)	Events retained post-flagging (step 4) (%)
Arroyo Seco	475	40	8	0	0	8	5	88	91	394	83
Ash Canyon Creek	497	48	10	0	2	8	4	75	78	374	75
Cache La Poudre	1681	186	11	1	23	6	5	80	93	1208	72
Camp Creek	361	123	34	1	56	2	0	42	88	162	45
Clear Creek	1219	105	9	3	8	9	13	77	89	885	73
Shitike Creek	881	102	12	4	19	0	16	62	93	663	75
Thompson River	602	75	12	3	4	1	8	67	91	449	75
Valley Creek	859	72	8	1	33	1	7	74	91	624	73
Wet Bottom Creek	451	23	5	0	22	0	4	70	100	282	63
Overall	7026	774	11	2	13	4	15	69	90	5041	72

Hydrologic control investigation

Table S6: Percent of rainfall-runoff events assigned to each hydrologic condition for the four hydrologic controls. No melt season was identified for Arroyo Seco and Wet Bottom Creek and only snow-off rainfall-runoff events were included in the antecedent precipitation conditions.

Watershed	Disturbance		Water year type		Season			Antecedent precipitation		
	Undisturbed (%)	Post-fire (%)	Dry (%)	Wet (%)	Melt (%)	Summer (%)	Winter (%)	None (%)	Low (%)	High (%)
Arroyo Seco	79	21	43	57	--	23	77	36	34	30
Ash Canyon Creek	70	30	20	80	41	12	47	42	56	2
Cache La Poudre River	77	23	27	73	31	47	21	15	78	7
Camp Creek	43	57	55	45	60	37	3	5	55	40
Clear Creek	80	20	19	81	24	35	41	23	70	7
Shitike Creek	76	24	11	89	51	13	36	29	34	37
Thompson River	65	35	19	81	47	13	39	28	65	7
Valley Creek	72	28	28	72	39	23	38	43	53	4
Wet Bottom Creek	70	30	16	84	--	31	69	36	35	29

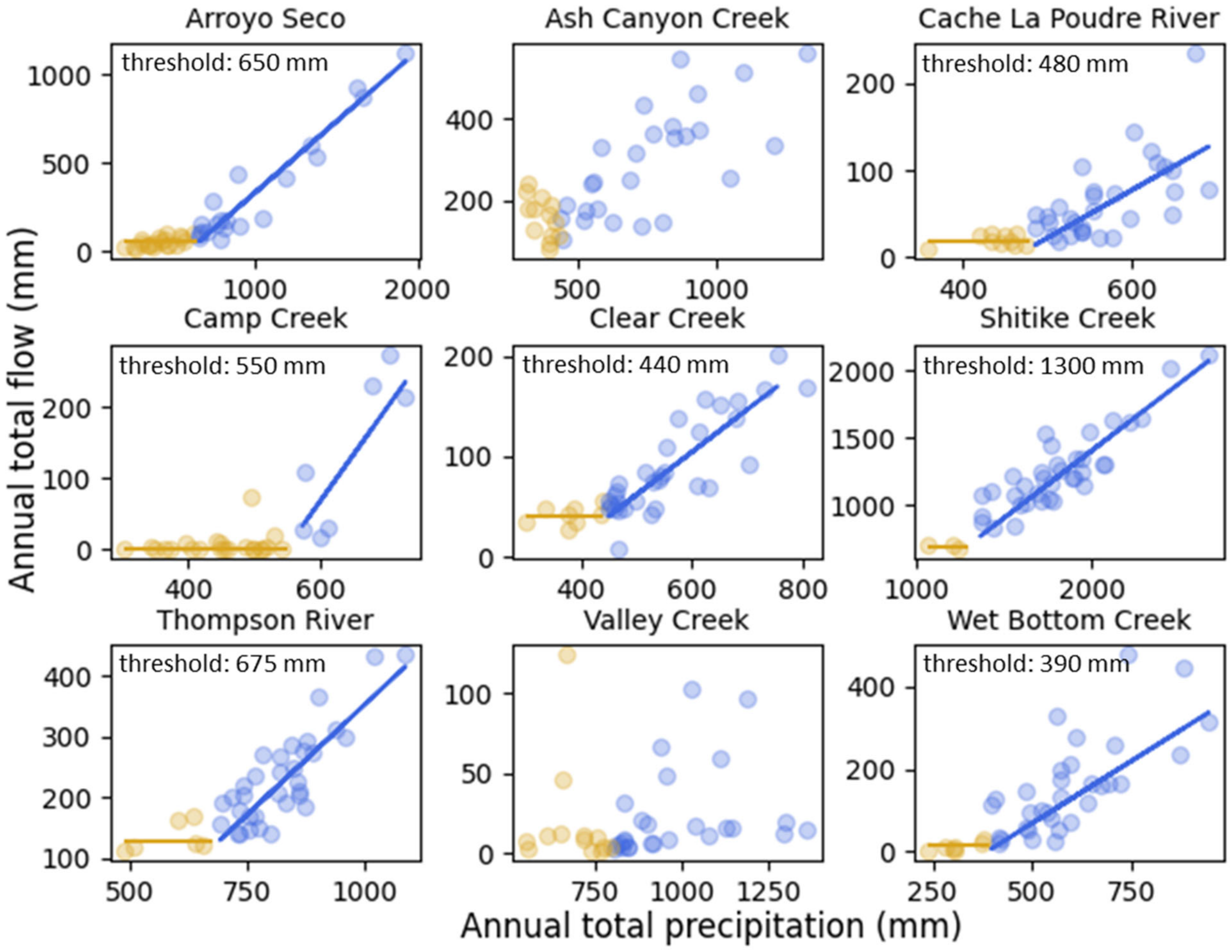

Figure S6: Wet and dry water year type conditions for all nine study watersheds. Where wet years are blue and dry years are orange. A watershed specific precipitation threshold is identified in the watershed average annual total precipitation and annual total streamflow for the undisturbed years. The ordinary least squares linear regression trend lines for above (wet, blue) and below (dry, orange) the threshold are shown. For two watersheds, Ash Canyon Creek and Valley Creek, no threshold behavior was identified, therefore the bottom third by total annual precipitation years are dry and the top two thirds are wet.

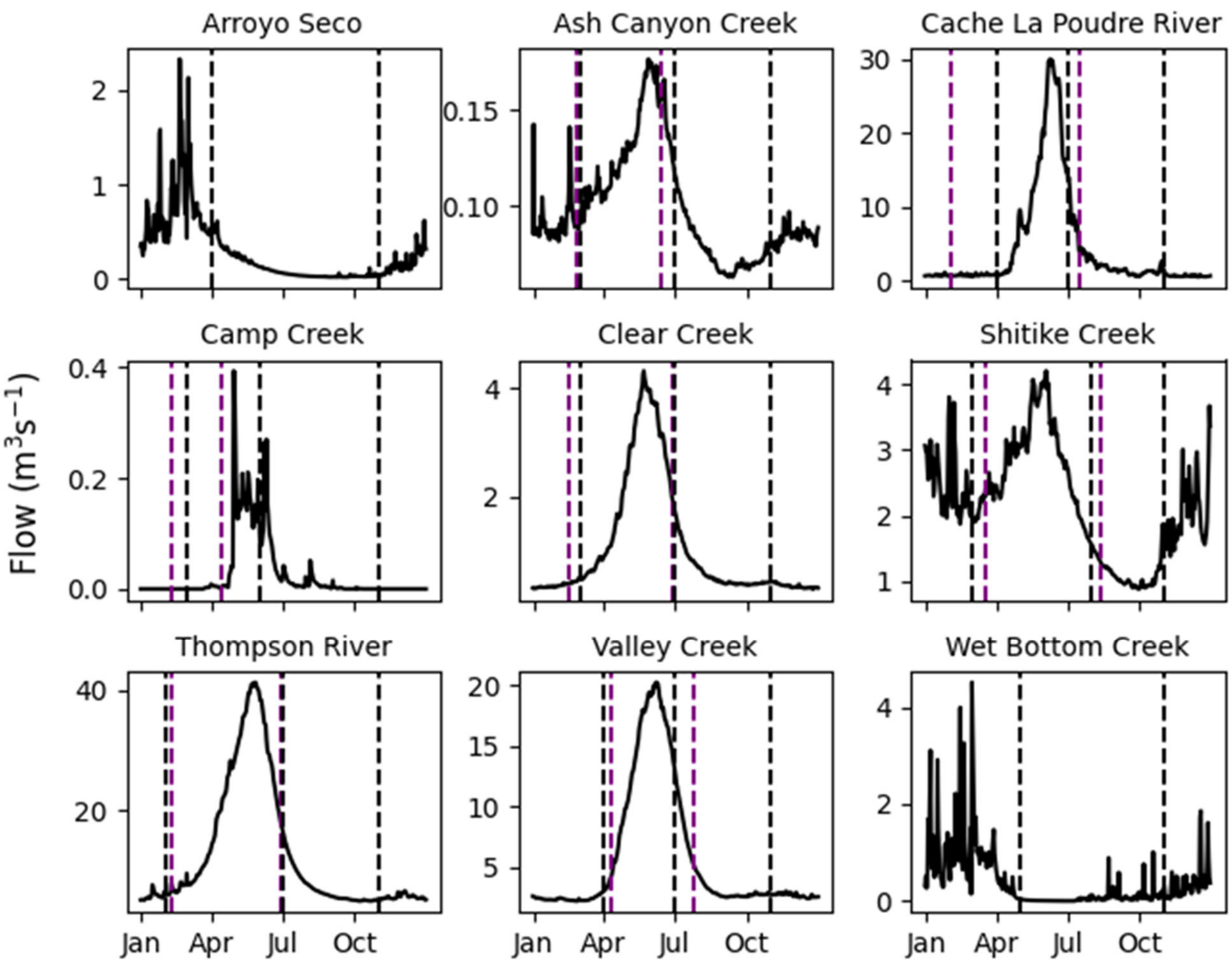

Figure S7: Season condition delineation for all nine study watersheds. Shown is the undisturbed average annual hydrograph. The seasons are delineated (black dashed) as the start of winter, start of melt, and start of summer consecutively for seven snow-dominated watersheds (Ash Canyon Creek, Cache La Poudre River, Camp Creek, Clear Creek, Shitike Creek, Thompson River, Valley Creek). The start of winter and start of summer are delineated consecutively for two non-snow (rain-dominated) watersheds (Arroyo Seco, Wet Bottom Creek). The minimum and maximum snow melt days within the watershed are consecutively shown (purple dashed).

Table S7: Undisturbed events Mann Whitney U Test p-value results for wet and dry conditions for the water year type time-varying hydrologic control. Shading indicates rejection of the null hypothesis at a significance level of 0.05.

Event metric	Arroyo Seco	Ash Canyon Creek	Cache La Poudre River	Camp Creek	Clear Creek	Shitike Creek	Thompson River	Valley Creek	Wet Bottom Creek
volume	<0.001	0.003	0.02	0.005	0.009	<0.001	0.02	0.81	0.1
RR	<0.001	<0.001	0.27	<0.001	0.003	0.02	0.12	0.19	0.05
peak	<0.001	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	0.16
Rise	<0.001	0.02	0.004	0.14	0.002	<0.001	0.02	0.43	0.28
Fall	<0.001	0.03	<0.001	0.02	<0.001	<0.001	<0.001	0.59	0.27
Rise_percent	<0.001	0.07	0.14	0.37	0.64	0.007	0.23	0.19	0.71
Fall_percent	<0.001	0.22	0.02	0.15	0.64	<0.001	0.1	0.04	0.57
RiseRate	<0.001	0.71	0.01	0.35	0.02	<0.001	0.04	0.7	0.65
FallRate	<0.001	0.1	<0.001	0.19	<0.001	<0.001	0.011	0.37	0.36
duration	0.05	0.1	0.09	0.04	0.56	0.24	0.08	0.5	0.07
rising_dur	0.008	0.05	0.44	0.82	0.19	0.03	0.1	0.08	0.04
falling_dur	0.48	0.99	0.2	0.012	0.48	0.5	0.12	0.58	0.36
RT1	0.005	0.13	0.13	0.85	0.6	0.14	0.06	0.62	0.56
RT2	0.5	0.41	0.02	0.53	0.34	0.006	0.2	0.013	0.23
T2P1	<0.001	0.4	0.9	0.78	0.14	0.13	0.05	0.04	0.09
T2P2	0.002	0.21	0.61	0.58	0.07	0.91	0.55	0.47	0.11
T2P3	0.93	0.2	0.36	0.48	0.06	0.3	0.62	0.39	0.63
volume_area	<0.001	0.003	0.02	0.005	0.009	<0.001	0.02	0.81	0.1
RR_area	<0.001	<0.001	0.27	<0.001	0.003	0.02	0.12	0.19	0.05
Peak_area	<0.001	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	0	0.16
Rise_area	<0.001	0.02	0.004	0.14	0.002	<0.001	0.02	0.43	0.28
Fall_area	<0.001	0.03	<0.001	0.02	<0.001	<0.001	<0.001	0.59	0.27

Rise_percent_area	<0.001	0.07	0.14	0.37	0.64	0.007	0.23	0.19	0.71
Fall_percent_area	<0.001	0.22	0.02	0.15	0.64	<0.001	0.1	0.04	0.57
RiseRate_area	<0.001	0.02	0	0.14	0.002	<0.001	0.02	0.43	0.28
FallRate_area	<0.001	0.03	<0.001	0.02	<0.001	<0.001	<0.001	0.59	0.27
duration_area	0.05	0.1	0.09	0.04	0.56	0.24	0.08	0.5	0.07
rising_dur_area	0.008	0.05	0.44	0.82	0.19	0.03	0.1	0.08	0.04
falling_dur_area	0.48	0.99	0.2	0.012	0.48	0.5	0.12	0.58	0.36
RT1_area	0.005	0.13	0.13	0.85	0.6	0.14	0.06	0.62	0.56
RT2_area	0.5	0.41	0.02	0.53	0.34	0.006	0.2	0.013	0.23
T2P1_area	<0.001	0.4	0.9	0.78	0.14	0.13	0.05	0.04	0.09
T2P2_area	0.002	0.21	0.61	0.58	0.07	0.91	0.55	0.47	0.11
T2P3_area	0.93	0.2	0.36	0.48	0.06	0.3	0.62	0.39	0.63
RR_volE	<0.001	0.69	0.003	0.06	0.21	0.06	0.02	0.06	0.54
Peak_volE	0.06	0.009	0.1	0.59	0.87	0.06	0.13	0.45	0.06
Rise_volE	0.74	0.04	0.86	0.001	0.95	0.71	0.7	0.74	0.45
Fall_volE	0.45	0.01	0.38	0.02	0.61	0.89	0.17	0.88	0.009
Rise_percent_volE	0.005	0.009	<0.001	0.43	0.006	0.06	0.21	0.15	0.26
Fall_percent_volE	<0.001	<0.001	<0.001	0.04	<0.001	0.001	0.02	0.17	0.002
RiseRate_volE	0.23	0.03	0.2	0.005	0.56	0.65	0.48	0.43	0.3
FallRate_volE	1.0	0.09	0.84	0.005	0.95	0.75	0.17	0.51	0.03
duration_volE	<0.001	0.001	0.03	0.007	0.003	<0.001	0.013	0.76	0.08

rising_dur_volE	<0.001	0.12	0.002	0.002	0.05	0.005	0.18	0.97	0.48
falling_dur_volE	<0.001	<0.001	0.09	0.007	0.001	<0.001	0.012	0.23	0.05
RT1_volE	<0.001	0.002	0.04	0.001	0.05	<0.001	0.92	0.91	0.05
RT2_volE	<0.001	0.55	0.04	0.36	0.12	0.22	0.15	0.04	0.37
T2P1_volE	<0.001	0.011	0.002	0.002	0.02	<0.001	0.09	0.7	0.1
T2P2_volE	0.03	0.81	<0.001	0.03	0.61	<0.001	0.65	0.42	0.56
T2P3_volE	0.09	0.02	<0.001	0.45	0.18	0.7	0.81	0.57	0.18

Table S8: Undisturbed events Kruskal Wallis Test p-value results for winter, melt, and summer hydrologic conditions for the season time-varying hydrologic control. Shading indicates rejection of the null hypothesis at a significance level of 0.05. In shaded cells, an indicator marks the significantly different condition and no indicator marks all conditions being significantly different from the Dunn Test.

Event metric	Arroyo Seco	Ash Canyon Creek	Cache La Poudre River	Camp Creek	Clear Creek	Shitike Creek	Thompson River	Valley Creek	Wet Bottom Creek
volume	0.48	0.88	<0.001	0.17	<0.001 *	0.85	<0.001	<0.001 *	0.008
RR	0.32	0.3	<0.001	0.43	<0.001 *	<0.001 ^	<0.001 ^	<0.001	0.06
peak	0.013	0.002 ^	<0.001	0.33	<0.001	<0.001	<0.001 ^	<0.001 ^	0.005
Rise	0.05	0.96	<0.001	0.51	<0.001	0.33	<0.001 ^	<0.001 ^	0.011
Fall	0.03	0.89	<0.001	0.17	<0.001	0.28	<0.001	<0.001	0.1
Rise_percent	0.04	0.2	<0.001	0.98	<0.001 #	0.001	0.82	0.1	0.14
Fall_percent	0.09	0.04	<0.001	0.05	<0.001	<0.001 ^	0.47	<0.001 #	0.04
RiseRate	0.02	0.42	<0.001	0.34	<0.001 ^	0.54	<0.001	<0.001 ^	0.27
FallRate	<0.001	0.78	<0.001	0.05	<0.001	0.02 #	<0.001 ^	<0.001	0.04
duration	0.15	0.35	0.04	0.61	<0.001 #	0.24	0.16	<0.001 #	0.23
rising_dur	0.7	0.27	0.99	0.36	0.001 *	0.84	0.58	0.33	<0.001
falling_dur	0.04	0.94	<0.001	0.92	<0.001 #	0.002	0.011	<0.001	0.26
RT1	0.47	0.04	0.87	0.19	<0.001 #	<0.001 #	0.005 #	0.02	0.28
RT2	0.45	0.28	0.65	0.9	0.014	0.008	0.34	0.006	0.36
T2P1	0.34	0.14	0.9	0.17	<0.001 #	0.75	0.95	0.38	0.001
T2P2	1.0	0.19	0.95	0.47	<0.001	0.24	0.17	0.09	0.006
T2P3	0.005	0.61	0.58	0.24	<0.001 #	<0.001 *	0.003 ^	0.002	0.4
volume_area	0.48	0.88	<0.001	0.17	<0.001 *	0.85	<0.001	<0.001 *	0.008
RR_area	0.32	0.3	<0.001	0.43	<0.001 *	<0.001 ^	<0.001 ^	<0.001	0.06
Peak_area	0.013	0.002 ^	<0.001	0.33	<0.001	<0.001	<0.001 ^	<0.001 ^	0.005
Rise_area	0.05	0.96	<0.001	0.51	<0.001	0.33	<0.001 ^	<0.001 ^	0.011

Fall_area	0.02	0.89	<0.001	0.17	<0.001	0.28	<0.001	<0.001	0.1
Rise_percent_area	0.04	0.2	<0.001	0.98	<0.001 #	0.001	0.82	0.1	0.14
Fall_percent_area	0.09	0.04	<0.001	0.05	<0.001	<0.001 ^	0.47	<0.001 #	0.04
RiseRate_area	0.05	0.96	<0.001	0.51	<0.001	0.33	<0.001 ^	<0.001 ^	0.011
FallRate_area	0.02	0.89	<0.001	0.17	<0.001	0.28	<0.001	<0.001	0.1
duration_area	0.15	0.35	0.04	0.61	<0.001 #	0.24	0.16	<0.001 #	0.23
rising_dur_area	0.7	0.27	0.99	0.36	0.001 *	0.84	0.58	0.33	<0.001
falling_dur_area	0.04	0.94	<0.001	0.92	<0.001 #	0.002	0.011	<0.001	0.26
RT1_area	0.47	0.04	0.87	0.19	<0.001 #	<0.001 #	0.005 #	0.02	0.28
RT2_area	0.45	0.28	0.65	0.9	0.014	0.008	0.34	0.006	0.36
T2P1_area	0.34	0.14	0.9	0.17	<0.001 #	0.75	0.95	0.38	0.001
T2P2_area	1.0	0.19	0.95	0.47	<0.001	0.24	0.17	0.09	0.006
T2P3_area	0.005	0.61	0.58	0.24	<0.001 #	<0.001 *	0.003 ^	0.002	0.4
RR_volE	<0.001	0.32	<0.001 *	0.28	<0.001 #	<0.001 ^	0.07	0.1	0.02
Peak_volE	0.6	0.34	<0.001 #	0.42	<0.001 #	0.1	0.26	<0.001 *	0.97
Rise_volE	0.001	0.2	0.03	0.07	<0.001 #	0.3	0.014	<0.001	0.42
Fall_volE	0.13	0.92	0.87	0.07	<0.001	0.76	0.12	<0.001 *	0.21
Rise_percent_volE	0.06	<0.001 ^	<0.001	0.95	<0.001	<0.001	<0.001 ^	<0.001	0.33
Fall_percent_volE	0.4	0.012 ^	<0.001	0.19	<0.001	<0.001	<0.001 ^	<0.001	<0.001
RiseRate_volE	0.06	0.05	0.26	0.06	0.004	0.06	0.011	<0.001 *	0.08
FallRate_volE	0.08	1.0	0.04	0.33	<0.001	0.28	0.08	<0.001	0.54
duration_volE	0.05	1.0	<0.001	0.14	<0.001 *	0.44	<0.001	<0.001	0.06

rising_dur_volE	0.2	0.11	<0.001	0.37	<0.001 *	0.02 #	<0.001	<0.001	0.47
falling_dur_volE	0.02	0.8	<0.001	0.09	<0.001	0.16	<0.001 ^	<0.001 ^	0.02
RT1_volE	0.29	0.03	<0.001 *	0.97	<0.001 ^	0.02	0.02	0.83	0.05
RT2_volE	0.89	0.17	0.008 *	0.13	<0.001	0.005 #	<0.001 *	<0.001 *	0.98
T2P1_volE	0.16	0.1	<0.001	0.44	<0.001 *	0.06	<0.001 ^	<0.001 *	0.08
T2P2_volE	0.74	0.08	<0.001	0.85	0.12	<0.001 #	<0.001 ^	<0.001 *	0.76
T2P3_volE	0.17	0.74	<0.001 *	0.05	0.08	<0.001 *	0.98	0.68	0.74

Seasons: *Winter, ^Melt, #Summer

Table S9: Undisturbed events Kruskal Wallis Test p-value results for none, low, and high hydrologic conditions for the antecedent precipitation time-varying hydrologic control. Shading indicates rejection of the null hypothesis at a significance level of 0.05. In shaded cells, an indicator marks the significantly different condition and no indicator marks all conditions being significantly different from the Dunn Test.

Event metric	Arroyo Seco	Ash Canyon Creek	Cache La Poudre River	Camp Creek	Clear Creek	Shitike Creek	Thompson River	Valley Creek	Wet Bottom Creek
volume	0.32	0.09	0.68	0.27	0.07	0.41	0.28	0.32	0.23
RR	0.1	0.1	0.98	0.3	0.02	0.68	0.28	0.26	0.35
peak	<0.001 +	0.84	0.007	0.71	0.11	0.19	0.09	0.07	0.66
Rise	0.33	0.27	0.77	0.78	0.61	0.1	0.16	0.68	0.44
Fall	<0.001 +	0.26	0.02	0.58	0.23	0.14	0.15	0.65	0.47
Rise_percent	0.66	0.14	0.25	0.73	0.49	0.12	0.16	0.27	0.16
Fall_percent	0.07	0.07	0.43	0.1	0.36	0.17	0.33	0.64	0.25
RiseRate	0.08	0.62	0.39	0.88	0.56	0.17	0.22	0.73	0.9
FallRate	<0.001 +	0.52	0.09	0.76	0.003 &	0.07	0.36	0.29	0.68
duration	0.57	0.41	0.61	0.15	0.003 &	0.87	0.39	0.05	0.26
rising_dur	0.04	0.49	0.2	0.39	0.008 +	0.68	0.76	0.09	0.1
falling_dur	0.18	0.84	0.54	0.3	0.002	0.68	0.17	0.08	0.35
RT1	0.12	1.0	0.05	0.85	0.008 &	0.34	0.14	0.43	0.13
RT2	0.02	0.48	0.49	0.58	0.15	0.58	0.14	0.99	0.6
T2P1	0.012	0.49	0.09	0.54	0.001 +	0.47	0.79	0.08	0.03
T2P2	<0.001 &	0.59	0.07	0.71	0.002 +	0.78	0.34	0.07	0.06
T2P3	0.003	0.47	0.03	1	0.02 +	0.3	0.22	0.04	0.49
volume_area	0.32	0.09	0.68	0.27	0.07	0.41	0.28	0.32	0.23
RR_area	0.1	0.1	0.98	0.3	0.02	0.68	0.28	0.26	0.35
Peak_area	<0.001 +	0.84	0.01	0.71	0.11	0.19	0.09	0.07	0.66
Rise_area	0.33	0.27	0.77	0.78	0.61	0.1	0.16	0.68	0.43

Fall_area	<0.001 +	0.26	0.02	0.58	0.23	0.14	0.15	0.65	0.47
Rise_percent_area	0.66	0.14	0.25	0.73	0.49	0.12	0.16	0.27	0.16
Fall_percent_area	0.07	0.07	0.43	0.1	0.36	0.17	0.33	0.64	0.25
RiseRate_area	0.33	0.27	0.77	0.78	0.61	0.1	0.16	0.68	0.43
FallRate_area	<0.001 +	0.26	0.02	0.58	0.23	0.14	0.15	0.65	0.47
duration_area	0.57	0.41	0.61	0.15	0.003 &	0.87	0.39	0.05	0.26
rising_dur_area	0.04	0.49	0.2	0.39	0.008 +	0.68	0.76	0.09	0.1
falling_dur_area	0.18	0.84	0.54	0.3	0.002	0.68	0.17	0.08	0.35
RT1_area	0.12	1.0	0.05	0.85	0.008 &	0.34	0.14	0.43	0.13
RT2_area	0.02	0.48	0.49	0.58	0.15	0.58	0.14	0.99	0.6
T2P1_area	0.012	0.49	0.09	0.54	0.001 +	0.47	0.79	0.08	0.03
T2P2_area	<0.001 &	0.59	0.07	0.71	0.002 +	0.78	0.34	0.07	0.06
T2P3_area	0.003	0.47	0.03	1.0	0.02 +	0.3	0.22	0.04	0.49
RR_volE	0.32	0.42	0.28	0.78	0.31	0.47	0.56	0.56	0.39
Peak_volE	0.41	0.12	0.56	0.05	0.03	0.56	0.41	0.19	0.65
Rise_volE	0.02	0.3	0.63	0.08	0.05	0.27	0.35	0.95	0.99
Fall_volE	0.02	0.23	0.63	0.05	<0.001 &	0.22	0.29	0.15	0.84
Rise_percent_volE	<0.001	0.35	0.02 +	0.33	0.02	0.53	0.07	0.28	0.06
Fall_percent_volE	0.02	0.22	0.47	0.21	<0.001 &	0.39	0.14	0.22	0.88
RiseRate_volE	0.07	0.53	0.77	0.17	0.06	0.88	0.5	0.77	0.72
FallRate_volE	0.09	0.26	0.76	0.18	0.001 &	0.33	0.31	0.11	0.63
duration_volE	0.01	0.06	0.41	0.46	0.74	0.23	0.18	0.49	0.7

rising_dur_volE	<0.001	0.3	0.07	0.67	0.002 +	0.48	0.13	0.33	0.76
falling_dur_volE	0.02	0.07	0.79	0.39	1.0	0.15	0.23	0.54	0.74
RT1_volE	0.004	0.21	0.13	0.31	0.88	0.11	0.18	0.99	0.32
RT2_volE	0.61	0.59	0.47	0.32	0.013	0.52	0.22	0.24	0.2
T2P1_volE	<0.001	0.21	0.13	0.42	0.013	0.32	0.18	0.72	0.6
T2P2_volE	<0.001	0.53	0.13	0.24	<0.001 +	0.26	0.13	0.68	0.53
T2P3_volE	0.08	0.61	0.1	0.36	0.004 +	0.08	0.05	0.02	0.24

Antecedent precipitation: &None, ~Low, +High

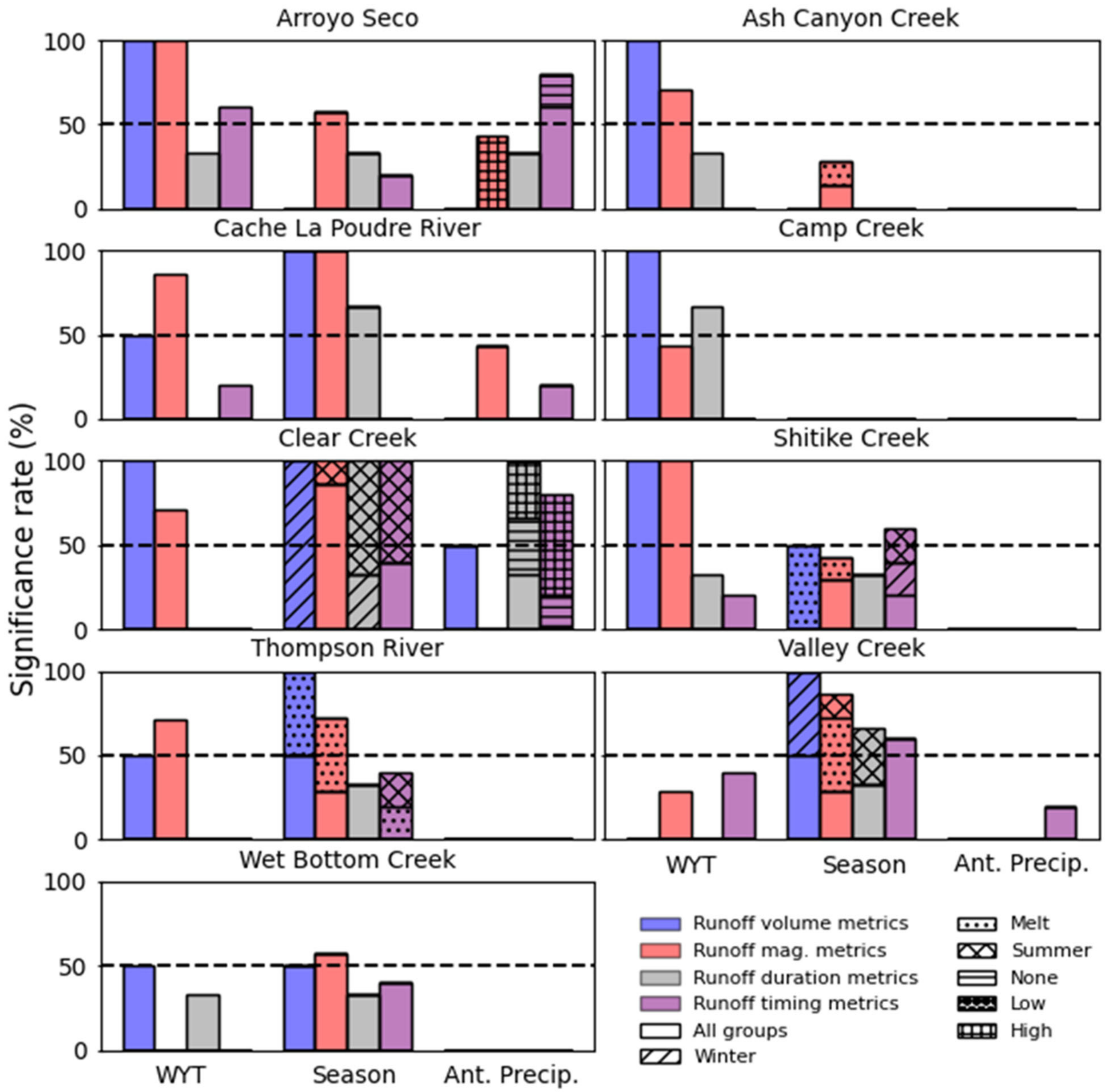

Figure S8: Event runoff metric group significance summary rates for statistical test results for area-normalized metrics. Individual plots for each study watershed. Shown are the average significance rates within the four rainfall-runoff metric groups including runoff volume metrics (blue), runoff magnitude metrics (red), runoff duration metrics (grey), and rainfall-runoff timing metrics (purple). Bars are grouped by time-varying hydrologic control (WYT, season, antecedent precipitation). The WYT group shows results of the Mann Whitney U Test. The season and antecedent precipitation groups show results from the Kruskal Wallis Test. The hatching within the bars represents statistically different individual hydrologic conditions from the Dunn Test where no hatching indicates all hydrologic conditions were statistically different. The 50% rate is highlighted (black dashed).

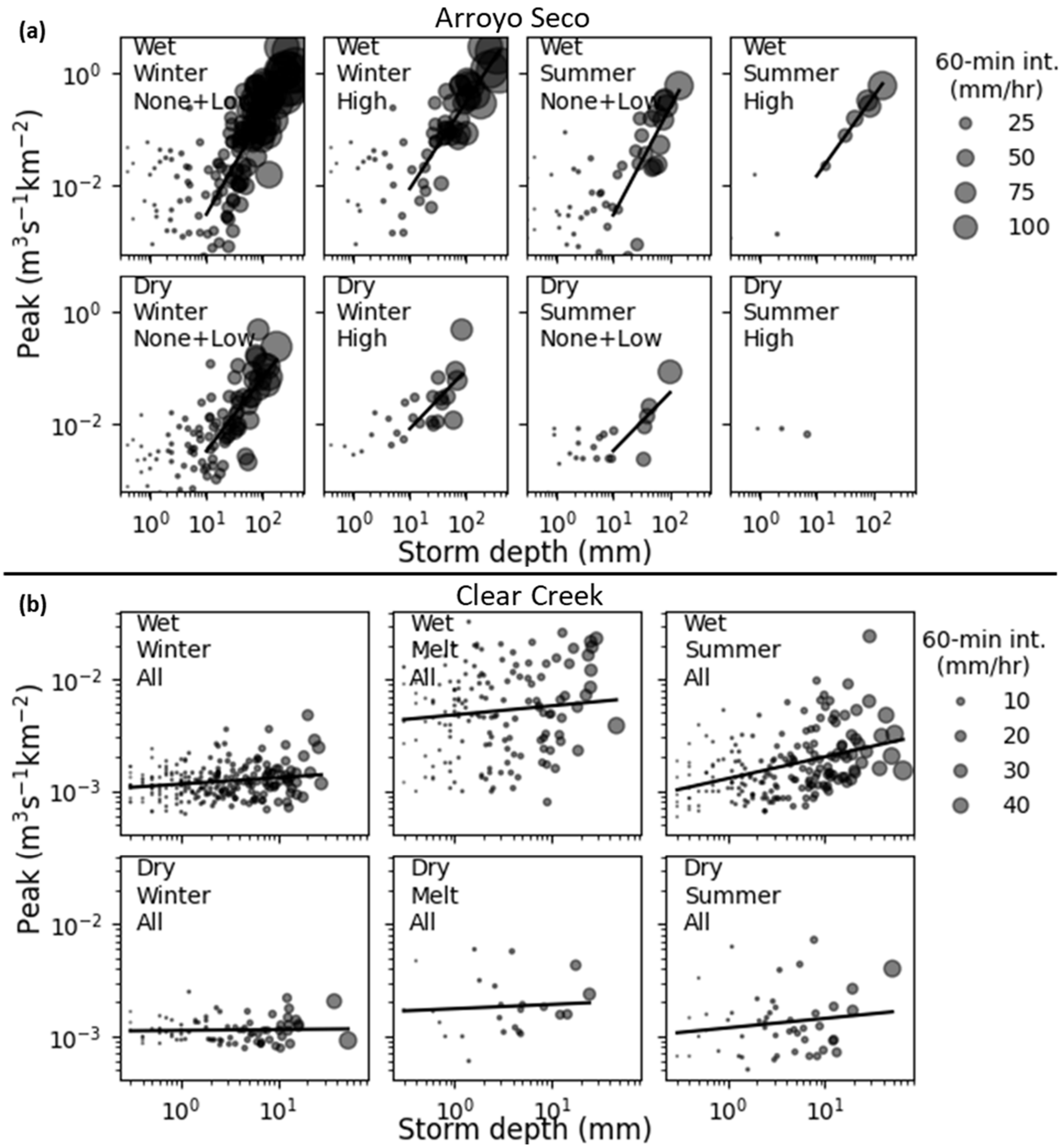

Figure S9: Hydrologic condition permutations for Arroyo Seco (a) and Clear Creek (b) for the storm depth (mm) and runoff peak (m^3 s^{-1} km^{-2}) relationship. Where undisturbed rainfall-runoff events and the permutation power trend are shown. Rainfall-runoff events are sized by 60-minute peak storm intensity (mm hr^{-1}).

Table S10: Power trend slope and intercepts in log-log space for significant condition groups for Arroyo Seco and Clear Creek for the storm depth (mm) and runoff peak ($m^3 s^{-1} km^{-2}$) relationship.

Group	Slope	Intercept
Arroyo Seco		
All	1.74	-9.89
Wet, None+Low	1.88	-10.63
Wet, High	1.54	-8.20
Dry	1.29	-8.69
Clear Creek		
All	0.080	-6.39
Summer	0.18	-6.67
Winter	0.041	-6.77
Wet, Melt	0.081	-5.33
Dry, Melt	0.038	-6.34

Table S11: Percent of post-fire events above the undisturbed trend line and plus one standard deviation for grouped events in Arroyo Seco and Clear Creek. Shading indicates percent at or above expected (50% for trend line, 16% for plus one standard deviation).

Year since fire		All	0	1	2	3	4	5	6
Arroyo Seco									
Wet, None + Low	Above trend line (%)	93	86	100	--	--	--	--	--
	Above +1 std. dev. (%)	57	71	43	--	--	--	--	--
Wet, High	Above trend line (%)	67	75	50	--	--	--	--	--
	Above +1 std. dev. (%)	33	50	0	--	--	--	--	--
Dry	Above trend line (%)	56	--	--	67	50	50	33	100
	Above +1 std. dev. (%)	7	--	--	0	0	0	11	25
Clear Creek									
Summer	Above trend line (%)	74	56	100	71	67	57	67	71
	Above +1 std. dev. (%)	26	44	47	6	8	29	67	14
Winter	Above trend line (%)	40	0	50	17	33	20	50	70
	Above +1 std. dev. (%)	10	0	0	0	22	0	0	30
Wet, Melt	Above trend line (%)	56	82	33	0	0	--	50	100
	Above +1 std. dev. (%)	20	45	0	0	0	--	0	0
Dry, Melt	Above trend line (%)	100	--	--	--	--	100	--	--
	Above +1 std. dev. (%)	43	--	--	--	--	43	--	--

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