Estimating Double Peak Streamflow Timing in the Uncompahgre River Using Snowpack Metrics

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Abstract
Water resources in the southern Rocky Mountains are driven primarily by snowmelt and rely on natural and artificial storage systems to deliver water throughout the year. However, climate driven changes to annual accumulation and melt patterns, specifically, decreases in maximum snow water equivalent (SWE) and earlier melt onset and peak streamflow dates, pose complications for water users and could increase runoff forecasting errors. This study focused on using snowpack metrics from high-elevation snow stations to forecast peak streamflow timing in the Uncompahgre River near Ridgeway, Colorado. This river system exhibits two peaks in streamflow during snowmelt and is an important tributary to the Colorado River basin. Daily streamflow data were used with snowpack data from Red Mountain Pass SNOTEL (RMP), Swamp Angel Study Plot (SASP), and Senator Beck Study Plot (SBSP) for water years 2005-2020 to (1) determine the correlation between two peak streamflow events and melt-out timing in sub-alpine and alpine basins, and (2) develop a linear forecasting model. The analysis used peak streamflow amounts and dates in the Uncompahgre River, peak SWE amount and date at RMP, peak depth amount and date at SASP and SBSP, and snow-all-gone dates at the three snow stations for each water year. The Nash-Sutcliffe Coefficient of Model of Efficiency (NSE) was used to evaluate both correlation and model fit. Snow all gone at Senator Beck Study Plot served as a good estimator of the second peak streamflow occurrence when the outlier years of 2009 and 2012 were removed (NSE= 0.82), while 50% peak SWE date at Red Mountain Pass proved the best estimator of the first peak streamflow occurrence (NSE=0.84) after removal of outlier years 2012 and 2020. The second peak streamflow occurrence was also successfully modeled using 50% peak SWE date at RMP (NSE=0.79), 50% peak depth date and SASP (NSE=0.77), and 50% peak depth date at SBSP (NSE=0.76).

Introduction

Over one-sixth of the global population, particularly communities in arid high-elevation regions like Colorado, depends on snowmelt for water supply and to support a suite of water-related industries (Barnett *et al.*, 2005, Dozier *et al.*, 2016). In the southern Rocky Mountains, 60-70% of annual precipitation falls as snow, fueling a multi-billion-dollar recreation industry, substantial agricultural needs, and consumptive use demands (Serreze *et al.*, 1999; Clow, 2010). This region relies heavily on natural and artificial (reservoir) storage to maintain water resources throughout the summer and early fall months (Barnett *et al.*, 2005). However, changes in climate driving altered accumulation and melt patterns are impacting the natural water storage capacity of seasonal snowpacks (Stewart *et al*., 2004; Knowles et al. 2006; Mote 2006; Clow, 2010).

Decreases in maximum snow water equivalent (SWE) and April 1st SWE have been observed across Colorado, with more pronounced changes in the western and southern mountain ranges (Clow, 2010; Fassnacht & López-Moreno, 2020). General trends indicate that snowmelt onset and peak streamflow date are occurring increasingly earlier in the season (Brown, 2000; Stewart *et al*., 2004; Clow, 2010; Kunkel *et al*., 2016; Musselman *et al*. 2017), posing complications for water resource managers, water rights holders, and recreation industries that depend on summer flows to maintain a viable business (Stewart et al., 2004; Clow, 2010). In 2012, the Natural Resource Conservation Service and the National Weather Service ceased coordinating their annual runoff forecasts, causing most western states to deliver on water rights claims using either the NRCS regression-based forecasts or the NWS River Forecast System's hydrologic model (Pagano *et al.*, 2014). These runoff-forecast models rely on temperature dependent snowmelt models that simplify the snowmelt process, producing variable and generally inconsistent streamflow results (Hock, 2003; Hock, 2005; Franz et al., 2008; Bryant *et al*., 2013; Follum et al., 2019). Changes in the snow surface energy balance regime driven by climate change, dust-on-snow events, black carbon, and other forcings could increase errors in forecasted runoff (Painter *et al.*, 2007; Milly *et al*., 2008; Dozier, 2011; Skiles *et al.*, 2012; Bryant *et al*., 2013). Basin-level forecasts methods, like those employed by the Colorado Basin River Forecast Center, can also produce substantial errors when downscaling to smaller basins (Pagano & Garen, 2006). It is also important to note that water laws in many western states require that prior appropriation water rights contain specific time of year limitations. Several interstate compacts also revolve around spring calendar dates to some extent (Kenney *et al*., 2008). As those changes discussed above continue to alter when key streamflow events occur in western states, water right claims previously established during peak flows could be impacted. Developing alternative or supplemental forecasting methods, particularly for smaller basins, provides clearer information to those water rights holders potentially impacted by changes in peak flow timing and ensures proper allocation of water resources as drought continues through the San Juan Mountain Range and the American Southwest (Cook *et al*., 2015; Williams *et al*., 2020).

Streamflow in the Uncompahgre River near Ridgway, Colorado, appears to peak twice during snowmelt (J. Derry, personal communication). Generally, snowmelt dominated headwater systems exhibit a singular large peak in streamflow occurring in late May or early June (Fassnacht *et al*, 2014), although double peak behavior in hydrographs has been documented for transient runoff regimes in the Pacific Northwest (Hamlet & Lettenmaier, 2007). However, similar behavior in snowmelt dominated watersheds like the Uncompahgre has not been investigated in detail. This investigation's central hypothesis is that the snow all gone date in the sub-alpine correlates well with the first peak streamflow occurrence while snow all gone in the alpine biome correlates with the second peak occurrence because these two biomes make up roughly equal proportions in the study basin's persistent snow zone (Figure A-4).

To investigate this hypothesis, this study defines a potential framework for estimating the occurrence of peak run-off events using snow disappearance and peak depth or peak SWE measured at high elevation sites, focusing specifically on streamflow in the Uncompahgre River near Ridgway Colorado, located upstream of Ridgway Reservoir. The objectives of this study are to (1) determine the correlation between the river's two peaks and melt-out timing in sub-alpine and alpine basins and (2) use correlations determined between snowpack variables and the two peaks to develop a linear model for forecasting the timing of peak flow events. Results provide useful information for water resource management in the area.

Study Area

The Uncompahgre River watershed in the southwestern Colorado San Juan Mountain range encompasses Montrose, Ouray, Delta, San Juan, Gunnison, Hinsdale, and San Miguel counties, serving as a primary source of irrigation and drinking water for those communities and supplying the Ouray Hydrodam and Ridgway Reservoir (Figure 1). Historic hard rock mining activity has heavily impacted both the landscape and water quality in headwater basins. Degradation of riparian and riverine habitat due to water quality changes and sedimentation as well as the future availability of water resources are also concerns (Uncompahgre, 2018). The snowpack in the Uncompahgre watershed typically exhibits longer accumulation periods, lower peak SWE values, later melt onset dates, and lower melt rates than basins in other North American snow regimes (Trujillo et al., 2014). This analysis targeted peak flow dynamics in the upper 13% (386 km^2) of the 2888 km^2 Uncompahgre river basin (HUC 14020006), which is dominated by forested land cover types. Elevation ranges from 2,096 meters at the study basin outlet in Ridgway to 4,297 meters at the peak of Mt. Sneffels. The area receives a mean of 823 mm of precipitation annually, most of which falls as snow <streamstats.usgs.gov>. The study area contains 600 water rights claims, 210 of which are ditch diversions and 108 that involve some manner of reservoir (Figure A-6). The snowpack data used are from three nearby stations: one NRCS Snow Telemetry Network (SNOTEL) site and a set of study plots representing the alpine and sub-alpine biome operated by the Center for Snow and Avalanche Studies (CSAS).

Figure 1. Location of Uncompahgre watershed (HUC 14020006), Red Mountain Pass SNOTEL, and Senator Beck Study Basin plots (see Table 1).
Figure 2. Land cover types of the upper Uncompahgre River watershed
Table 1. Station metadata, period of record, and variables used for USGS station Uncompahgre near Ridgway, Red Mountain Pass (RMP) SNOTEL, Senator Beck Study Plot (SBSP), and Swamp Angel Study Plot (SASP).

Data

Historic daily discharge data were obtained from USGS station 09146200 (Uncompahgre near Ridgway) for water years 1981-2020. The station is located 3.7 kilometers north of Ridgway, Colorado, in Ouray County and is managed by the United States Geologic Survey (USGS). Peak streamflow and peak streamflow date were extracted for each water year (Figure 3), defined as 01 October of the previous year to 30 September of the current year. For example, water year (WY) 2005 represents 01 October 2004 to 30 September 2005.

Hydrographs in the Uncompahgre across most water years exhibited two peaks after the initiation of melt at Red Mountain Pass SNOTEL (RMP), suggesting that two distinct melt events occur in the persistent snow zones upstream of USGS station 09146200 (Figure 4).

Figure 3. Peak streamflow and peak streamflow date for water years 1981-2020 in the Uncompahgre near Ridgway (USGS 09146200).

Figure 4. Hydrographs for USGS station 09146200 for water years 2005 and 2009 representing examples of double peak behavior in the Uncompahgre River near Ridgway, CO.

Historic snow water equivalent (SWE) data for water years 1981-2020 was obtained from Snow Telemetry (SNOTEL) site 713 near Red Mountain Pass located in San Juan County, Colorado. The SNOTEL network was established in 1977 to provide hourly or sub-hourly snow and weather data to the Snow Survey and Water Supply Forecasting Program (SSWSF), now housed in the Natural Resource Conservation Service (NRCS) National Water and Climate Center (USDA, 2012). Peak SWE and peak SWE date were extracted for each water year (Figure 5).

Figure 5. Maximum snow water equivalent (SWE) and maximum SWE date for the period of record (WY1981-WY2020) at Red Mountain Pass SNOTEL station (site id 713).

Snow depth data for water years 2005 to 2020 were obtained from the Center for Snow and Avalanche Studies (CSAS) <snowstudies.org> Senator Beck Study Plot (SBSP) and Swamp Angel Study Plot (SASP) in Senator Back Basin study area just north of Red Mountain Pass (Table 1). These two stations represent snowpack dynamics in the two dominant biome types in the study basin: alpine (SBSP) and sub-alpine forest (SASP). The non-profit Center for Snow and Avalanche Studies was established in 2003 as a mountain hydrology research center and collects hourly wind, temperature, radiation, relative humidity, soil moisture, soil temperature, and snow depth data for each site (Landry *et al.*, 2014). Peak depth and peak depth date at each site were extracted for each water year (Figure 6).

Figure 6. Maximum depth and maximum depth date for the period of record (WY2005-WY2020) at Colorado Snow and Avalanche Studies Swamp Angel Study Plot (top) and Senator Beck Study Plot (bottom). Data obtained from <www.snowstudies.org>

Methodology

Using the hydrographs from the Uncompahgre River near Ridgway from WY 2005-2020, date and streamflow values for each of the two peaks for each water year were manually extracted. Peaks were considered if they occurred after 80% of peak SWE (i.e. during melt) and on or before July 1. For peaks to be considered distinct, streamflow values must have dropped to 50% of the previous peak before increasing again. Four of the fifteen years examined exhibited three distinct peaks (Figure A-1). In these instances, the two representing the highest streamflow values were used for analysis. These peak events were organized based on their occurrence in time (i.e. peak 1 represents the first peak flow event to occur in that water year).

Snow all gone (SAG) dates at SBSP, SASP, and SNOTEL station 713 (RMP); peak SWE amount and date at RMP, peak depth amount and date at SASP and SBSP, were extracted for WY2005 to WY2020 (Table 2). Although the period of record, or PoR, for the streamflow gauging station (PoR 1958-2020) and SNOTEL station (PoR 1981-2020) were much longer (Table 1), analyses were limited to the last 16 water years (2005-2020) to correspond with the data record at SASP and SBSP.

Since peak SWE and peak depth values persisted for two to five days during any given water year (Figure 7), the earliest date was selected to represent the peak occurrence. The date of snow disappearance, or snow all gone (SAG) (Skiles et al., 2012; Duncan, 2020), was calculated for each station as the first date after peak SWE at RMP or depth at SBSP and SASP recorded a SWE or depth value of zero.

Table 2. Summary statistics for peak SWE amount and date at Red Mountain Pass SNOTEL (RMP), peak depth amount and date for Swamp Angel Study Plot (SASP) and Senator Beck Study Plot (SBSP), and snow all gone (SAG) dates at all three stations based on each station's period of record.

Figure 7. Peak SWE duration for WY2005 (2 days), WY2008 (3 days), and WY2013 (5 days) at Red Mountain Pass SNOTEL

Linear regression plots of peak discharge date and snow all gone date at the three snow stations were generated and visually inspected for correlation and proximity to 1:1 line, indicating that SAG date models peak streamflow date reasonably well. The Nash-Sutcliffe model efficiency coefficient (NSE), as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Y_{obs} - Y_{mod})^2}{\sum_{i=1}^{n}(Y_{obs} - \overline{Y_{obs}})^2}$$

where Y_{obs} was defined as observed peak flow date and Y_{mod} was defined as SAG date, was used to quantify 1:1 fitness. NSE values generally range from NSE<0 (indicating that the mean observed value is a better estimator that the model) to NSE=1 (indicating a perfect modeled to observed fit) (Nash & Sutcliffe, 1970). Other snowpack variables, such as RMP peak SWE amount and date, RMP 50% peak SWE amount and date, SASP and SBSP peak depth amount and date, and SASP and SBSP 50% peak depth and date, were used to explain residual variation.

For the purposes of estimating peak 1 occurrence, explaining residual variation, and developing a simple linear model, 50% peak SWE and 50% peak depth were used as arbitrary markers for melt period. In higher elevation Colorado basins, large spring precipitation events are not uncommon and can potentially sustain peak SWE, or close to peak SWE values, for several weeks before substantial melt begins (Serreze *et al*., 2001; Fassnacht *et al*., 2014). The 50% maximum SWE date for RMP and 50% maximum depth for SASP and SBSP generally fall during the period of continuous, large scale decreases in SWE, indicating substantial melt (Figure 8). For the purposes of estimating runoff timing, utilizing these metrics in place of true peak snowpack values reduces potential errors introduced by local increases in SWE and depth during spring storms.

Figure 8. Depth at Senator Beck Study Plot (SBSP) and snow water equivalent at Red Mountain Pass SNOTEL site 713 (RMP) for waters years 2014, 2015, and 2016 justifying use of 50% maximum depth and date and 50% maximum SWE and date as markers of melt.

Correlations between SAG and 50% peak depth/SWE date at the three snow stations and linear regression results for SAG vs. peak flow were used to develop three simple linear models to estimate peak flow dates. Linear regression equations for SAG vs. peak 2 date for each station were substituted into the respective linear regression equation for 50% peak SWE date or 50% peak depth date vs. SAG.

Results[K1][F2]

Before removal of outlier years, correlation coefficients were similar across all six scenarios involving snow all gone date and model efficiency measured by the NSE was low (Figure A-5). However, after outlier year removal, snow all gone data at Senator Beck Study Plot proved the best estimator of the second peak streamflow date while the date of 50% SWE at Red Mountain Pass proved the best estimator for the first peak streamflow date (Figure 10c, Figure 11a). Snow all gone dates [K3][F4]were successfully estimated by 50% depth and SWE dates at the three stations, resulting in satisfactory linear models of peak 1 and peak 2 dates based on snow depth and SWE data (Figure 11, Figure 12).

Second peak streamflow

For peak 2 vs. SAG correlation, two outlier years (2009 and 2012) impacted SAG modeled fit. Across all three stations, SAG in these two years occurred substantially earlier than peak 2 date (33 days for 2009 and 15 days for 2012), particularly compared to the mean (5 days earlier for RMP, 8 days earlier for SASP, and 0 days earlier for SBSP). Their removal from correlation calculations increased correlation coefficient values and significantly increased NSE model efficiency values for scenarios involving peak 2 (Table 3). Peak 1 measures of fit were not substantially affected.

Table 3. Correlation coefficient (R^2) and Nash-Sutcliffe model efficiency coefficient values before and after outlier years (2009 and 2012) were removed for correlations between snow all gone dates (SAG) at SNOTEL site 713 (RMP), Swamp Angel Study Plot (SASP), and Senator Beck Study Plot (SBSP) and the two peak flow event dates in the Uncompahgre river near Ridgway, Colorado (USGS station 09146200).

Senator Beck Study Plot (SBSP) snow all gone date appeared to match the second peak flow occurrence date better than either Swamp Angel Study Plot (SASP) or Red Mountain Pass SNOTEL site 713 (RMP) (Figure 10, Table 3). This is consistent with the hypothesis that the second peak in Uncompahgre River discharge correlates with melt out in alpine biome basins. It is interesting to note that SBSP (the station representing the alpine biome) melted out before RMP five out of the 15 years examined and before SASP four out of the 15 years examined. However, this is most likely indicative of the relative locations of the individual stations rather than wide-spread alpine basin snow disappearance proceeding sub-alpine snow disappearance. Although SAG at Swamp Angel Study Plot (SASP) proved the poorest model of peak 2 occurrence (NSE=0.69), SAG occurred on or before the second peak streamflow event in all years except 2018. At Swamp Angel Study Plot, 20.5% of residual variation is explained by the date of 50% maximum depth at the site and 24.6% by days to melt (snow all gone date –

date of 50% maximum depth). At Senator Beck Study Plot, 20.2% of residual variation is also explained by date of 50% maximum depth at the site.

Figure 10. Correlations (omitting 2009 and 2012) between snow all gone (SAG) at (a) Red Mountain Pass SNOTEL station 713 (RMP), (b) Swamp Angel Study Plot (SASP), and (c) Senator Beck Study Plot (SBSP) and the second peak flow event to occur in the Uncompahgre River near Ridgway, CO (USGS 09146200).

First peak streamflow

The first peak discharge occurrence appears to correlate better and have stronger 1:1 fit with 50% maximum SWE date at RMP and 50% maximum depth date at SASP and SBSP than with snow all gone dates, particularly when outlier years (2012 and 2020) were removed (Figure 11, Table 4, Figure A-5). This is consistent with relatively high correlation values between residuals of peak 1 vs. SAG and 50% maximum depth at SASP and SBSP (R^2= 0.38 for SASP and R^2= 0.36 for SBSP). Model efficiency (NSE) for peak 1 date vs. 50% peak date at RMP (NSE=0.84) and SBSP (NSE= 0.81) was comparable to that for peak 2 vs. SAG. According to guidelines for interpreting NSE set forth by Morasi *et al.* 2007, 50% peak SWE at RMP and 50% depth at SBSP dates are considered satisfactory models of peak 1 date without outlier removal (NSE=0.523 and 0.511 respectively), while SAG is only a satisfactory model for peak 2 date after outlier years are removed.

Figure 11. Correlation between (a) 50% maximum SWE at Red Mountain Pass SNOTEL station 713 (RMP), (b) 50% maximum depth at Swamp Angel Study Plot (SASP), and (c) 50% maximum depth at Senator Beck Study Plot (SBSP) and the first peak flow event to occur in the Uncompahgre River near Ridgway, CO (USGS 09146200). Years 2012 and 2020 omitted from reported R^2 and NSE values.

Table 4. Nash-Sutcliffe model efficiency coefficient values before and after outlier years (2012 and 2020) were removed for correlations between 50% maximum SWE date at SNOTEL site 713 (RMP) and 50% maximum depth date at Swamp Angel Study Plot (SASP), and Senator Beck Study Plot (SBSP) and the first peak streamflow event in the Uncompahgre river near Ridgway, Colorado (USGS station 09146200).

Modeling peak occurrence

Based on NSE guidelines set forth by Morasi *et al.* (2007), peak 1 date appears to be well modeled by 50% peak SWE date at RMP (NSE=0.84) and nearly as well modeled by 50% depth date at SBSP (NSE=0.81) (Figure 11). Using 50% depth date at SBSP to directly model SAG was successful (NSE=0.75). However, 50% SWE date at RMP and 50% depth date at SASP were not satisfactory direct estimators of SAG (NSE= -1.09, NSE= -3.32 respectively) and were adjusted to better model the desired quantity. The addition of 13 days to RMP 50% SWE date and 23 days to SASP 50% depth date significantly improved model performance (NSE=0.82 for both) (Figure A-3). These relationships were then used to produce a series of satisfactory models for peak 2 occurrence (Figure 12).

Figure 12. Modeled peak 2 occurrence in the Uncompahgre near Ridgway using (a) 50% depth date at Red Mountain Pass SNOTEL (RMP), (b) 50% depth at Swamp Angel Study Plot (SASP) and (c) 50% depth at Senator Beck Study Plot (SBSP). Both the model equation/ NSE model fit and linear regression equation/R^2 information is presented.

Discussion

Traditionally, nation-wide water supply forecasts are issued by the Natural Resource Conservation Service (NRCS) and the National Weather Service (NWS) based on temperature-and-precipitation-based models (Pagano *et al.*, 2014). However, multiple studies have demonstrated the variability of the air temperature-melt relationship (Hock, 2003; Franz et al., 2008; Bryant et al., 2013; Follum et al., 2019). Annual peak flow estimation errors in the West range from 5-10%, with runoff forecasting errors during hydrographs' rising limbs reaching as high as 40% (Bryant *et al.*, 2013; Pagano *et al.*, 2014). Indeed, Painter *et al.* 2018 showed the rising limb of the Colorado River hydrograph to be insensitive to air temperature and driven primarily by different radiative forcers (dust, black carbon, etc). In Colorado and other snowmelt dominated water regimes, the rising limb of a hydrograph typically equates with sharp declines in SWE and snow depth in the mountains. Using SWE, depth, and snow disappearance metrics—such as those presented in this study—in runoff forecasting could help reduce forecasting errors, thereby benefitting water resource users.

This study suggests that simple snowpack metrics such as the date that 50% maximum SWE, 50% maximum depth, and snow all gone occur estimate peak flow occurrences in the Uncompahgre River reasonably well. Generally, Red Mountain Pass SNOTEL site metrics (50% maximum SWE date and SAG) were satisfactory models for peak 1 and 2 respectively (NSE= 0.837, 0.729). However, SAG at Senator Beck Study Plot better explained peak 2 occurrence (NSE= 0.821) and 50% maximum depth date at SBSP was almost as adept as RMP 50% maximum SWE at estimating peak 1 occurrence (NSE= 0.807). Depth and SAG metrics at Swamp Angel Study Plot, the sub-alpine site coupled with SBSP in the Senator Beck Study Basin, proved to be the poorest estimators of peak 1 and peak 2 occurrence, although SAG at SASP still acted as a satisfactory estimator for peak 2 (NSE=0.689) (Morasi *et al.* 2007). [K5]

Although these findings prove useful for estimating the occurrence of peak streamflow in the Uncompahgre, they do not fully explain the mechanism driving this dual peak behavior. Snow all gone at the sub-alpine stations (RMP and SASP) did not correlate well with peak 1 date, while data from all three sites regardless of biome produced satisfactory NSE values when used to estimate peak 2 date. However, the station located in the alpine biome (SBSP) proved the best estimator of peak 2. This suggests that while melt-out timing from the alpine biome is an important contributor to peak 2 occurrence and serves as the best estimator for that event, other processes are most likely driving double peak behavior in the Uncompahgre River. Melt-out timing discrepancies between N-NE facing aspects and S-SW facing aspects offers one potential explanation. Other studies have shown maximum snow accumulation and annual snowpack duration to be sensitive to changes in radiative forcing driven by changes in aspect, although none have attempted to correlate melt out on different aspects with peak streamflow (López-Moreno *et al.*, 2013, Jost *et al.*, 2007).

Another potential explanation is that melt-out in the two biomes estimates peaks based on magnitude. All relationships addressed in this study rely on a time-based division of the two Uncompahgre river peak streamflow events. Peak flow events could also be organized based on relative magnitude (i.e. peak 1 represents the largest peak flow event of the year), however, correlations and fit to the 1:1 model line seemed to be poor (Figure A-2) and NSE coefficients between snow all gone dates at all stations and peak events were low (NSE<0.4). Given that organizing peak events based on date of occurrence is comparatively more useful for water managers, this analysis focused on time-based organization.

Although snow all gone date serves as a satisfactory model of peak two occurrence, SAG date has less utility than SWE or depth metrics when forecasting streamflow. The relatively strong relationship between peak 1 occurrence and those same depth or SWE metrics (50% maximum depth date and 50% maximum SWE date) supports developing models based on those metrics. Constructing such models for peak 2 using 50% maximum depth date at SASP and SBSP and 50% maximum SWE date at RMP proved successful. Model efficiency values (NSE) ranged from 0.76 to 0.79 for the three models of peak 2 occurrence developed and 0.81 to 0.84 for the two satisfactory models of peak 1 occurrence (Figure 10, Figure 12). Snow all gone at SASP does not lend itself well as a direct estimator of peak 2 when compared to SAG at other stations, but it may still be useful from a forecasting standpoint. SAG at this station occurred before peak 2 in all water years except 2018.

Considering water years 2009 and 2012 illustrates the additional importance of considering dust on snow events when forecasting runoff. These two water years had the highest number of dust-on-snow events for the 2005-2019 period (Duncan, 2020) and exhibited melt out dates 14 to 25 days earlier than the average SAG date at each station. When using SAG to model peak 2, these two years also significantly impacted model performance. Water year 2012 also exhibited the lowest maximum discharge and second lowest maximum SWE value across the fifteen-year study period (11.0 m^3/s and 452.12 mm respectively) (Figure 3, Figure 5). However, water year 2018 exhibited similar peak discharge and maximum SWE values (Q_{max}= 11.0 m^3/s and SWE_{max}= 416.56 mm) and did not appear to affect model fit while the comparatively normal 2009 water year (Q_{max}= 31.7 m^3/s; SWE_{max}= 698.5 mm) did. Deposited dust has previously been shown to decrease snow cover duration and accelerate melt in Senator Beck Basin (Painter *et al.*, 2007; Skiles *et al*., 2012; Painter *et al.*, 2018; Duncan, 2020) and it is likely that these outlier years are better explained by dust on snow impacts than by snowpack and streamflow characteristics.

The relative success in using the Red Mountain Pass (SNOTEL site 713) SWE data to estimate both the first and second peak discharge events in the Uncompahgre bodes well for the development of similar models in other Colorado watersheds. Although snow depth data are also available at most SNOTEL sites, automated data collection began relatively recently compared to SWE data collection. Using snow water equivalent data allows this method to extend back longer and further hone model fit. However, the results of this study also highlight the power of utilizing data collected in alpine biomes, as metrics developed using the Senator Beck Study Plot depth data performed as well as RMP in estimating the first peak occurrence (NSE= 0.807 vs 0.837) and better in estimating the second peak occurrence (NSE=0.821 vs. 0.792). SNOTEL sites are typically located in sub-alpine biomes (at or below tree line) and so simulate alpine snowpack accumulation, melt, and their subsequent impact on streamflow dynamics less reliably. In river basins that contain relatively large expanses of alpine like the upper Uncompahgre, coupled monitoring sites in both the sub-alpine and alpine biomes becomes more important. Although melt out in the sub-alpine (represented by SAG at SASP and RMP) does not appear to be a good estimator of the first peak occurrence, melt out of alpine basins (represented by SAG at SBSP) represents an excellent estimator of the occurrence of the second peak discharge event.

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Data Access

SNOTEL daily data for Red Mountain Pass (site 713) are collected by the Natural Resource Conservation Service Water and Climate Center and are accessible from < https://www.wcc.nrcs.usda.gov/>. Depth data for Senator Beck Basin study plots (Swamp Angel Study Plot and Senator Beck Study Plot) are collected by the Center for Snow and Avalanche Studies and are archived at <https://snowstudies.org/ >. Daily streamflow data for the Uncompahgre near Ridgway, CO (USGS 09146200) can be found at <https://waterdata.usgs.gov/nwis/>.

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Table 1. Station metadata, period of record, and variables used for USGS station Uncompahgre near Ridgway, Red Mountain Pass (RMP) SNOTEL, Senator Beck Study Plot (SBSP), and Swamp Angel Study Plot (SASP).

Station	**Location**	**Latitude (N)**	**Longitude (W)**	**Elevation (m)**	**Aspect**	**Variable**	**Period of record**
USGS 09146200	Uncompahgre River near Ridgway	38.1842	107.7453	2096	--	Daily discharge	1958-2020
SNOTEL 713	Red Mountain Pass	37.90	107.72	3413	W	Snow water equivalent (SWE)	1981-2020
Senator Beck Study Plot (SBSP)	Senator Beck Basin Study Area, Red Mountain Pass	37.9069	107.7263	3714	NE	Snow depth	2005-2020
Swamp Angel Study Plot (SASP)	Senator Beck Basin Study Area, Red Mountain Pass	37.9069	107.7113	3371	NE	Snow depth	2005-2020

Table 2. Summary statistics for peak SWE amount and date at Red Mountain Pass SNOTEL (RMP), peak depth amount and date for Swamp Angel Study Plot (SASP) and Senator Beck Study Plot (SBSP), and snow all gone (SAG) dates at all three stations based on each stations period of record.

	RMP			**SASP**			**SBSP**		
	SAG	**Peak SWE (mm)**	**Peak SWE date**	**SAG**	**Peak depth (m)**	**Peak depth date**	**SAG**	**Peak depth (m)**	**Peak depth date**
Mean	6/8 ± 11 days	686± 171	4/23 ± 15 days	6/5 ± 14 days	2.28 ± 0.41	3/27± 17 days	6/12 ± 13 days	1.85 ± 0.47	4/18 ± 22 days
Range	51 days	752	64 days	45 days	1.51	55 days	48 days	1.91	71 days

Table 3. Correlation coefficient (R^2) and Nash-Sutcliffe model efficiency coefficient values before and after outlier years (2009 and 2012) were removed for correlations between snow all gone dates (SAG) at SNOTEL site 713 (RMP), Swamp Angel Study Plot (SASP), and Senator Beck Study Plot (SBSP) and the two peak flow event dates in the Uncompahgre river near Ridgway, Colorado (USGS station 09146200).

	All years (WY 2005-2020)		**Outliers (2009, 2012) removed**	
Snow all gone	**R^2**	**NSE**	**R^2**	**NSE**
First streamflow peak date				
RMP	0.67	-0.85[K6][F7]	0.65	-1.14
SASP	0.58	-0.49	0.56	-0.66
SBSP	0.62	-2.28	0.60	-2.89
Second streamflow peak date				
RMP	0.56	0.23	0.84	0.79
SASP	0.57	-0.12	0.88	0.69
SBSP	0.43	0.16	0.91	0.82

Table 4. Nash-Sutcliffe model efficiency coefficient values before and after outlier years (2012 and 2020) were removed for correlations between 50% maximum SWE date at SNOTEL site 713 (RMP) and 50% maximum depth date at Swamp Angel Study Plot (SASP), and Senator Beck Study Plot (SBSP) and the first peak streamflow event in the Uncompahgre river near Ridgway, Colorado (USGS station 09146200).

50% peak SWE date	**NSE (WY 2005-2020)**	**NSE (outliers 2012, 2020 removed)**
RMP	0.52	-1.14
50% peak depth date		
SASP	-2.17	-0.66
SBSP	0.51	-2.89

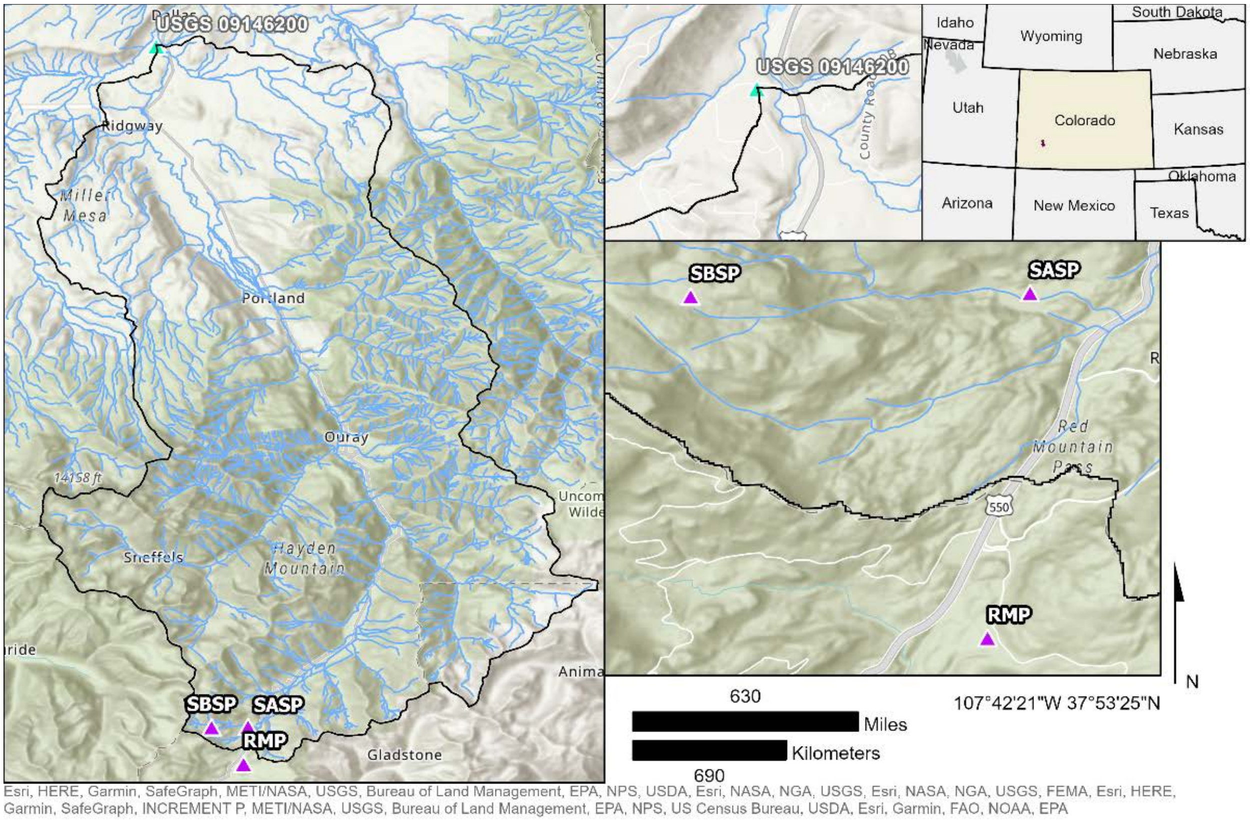
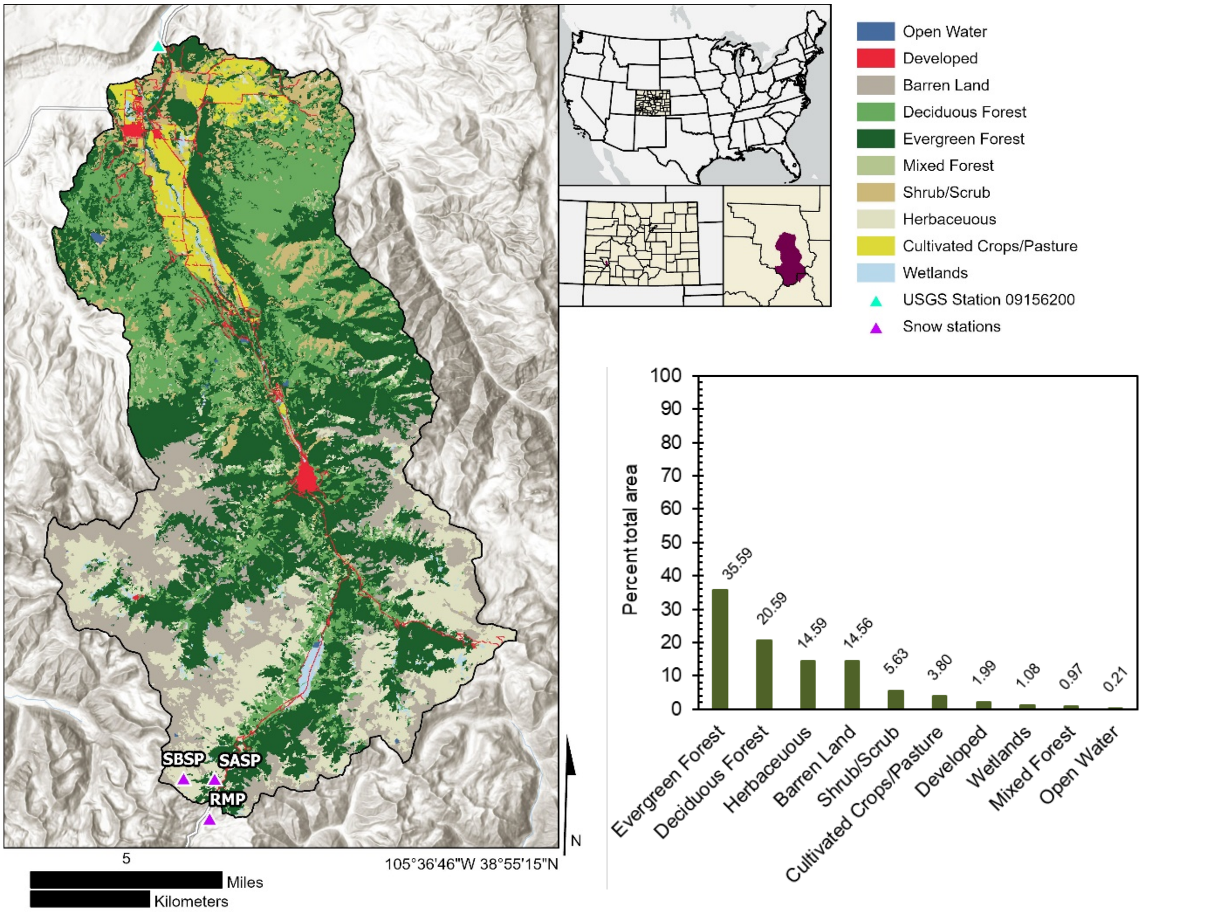


Figure 1. Location of Uncompahgre watershed (HUC 14020006) and relevant snow and streamflow stations (see Table 1). Data retrieved from Esri and National Hydrography Dataset.



Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, USDA, Esri, NASA, NGA, USGS, Esri, FAO, NOAA, Esri, HERE, Garmin, FAO, NOAA, NOAA, USGS, Bureau of Land Management, EPA, NPS, Esri, Garmin, FAO, NOAA, EPA

Figure 2. Upper Uncompahgre River watershed (386 km^2) landcover types based on the 2016 National Landcover Dataset

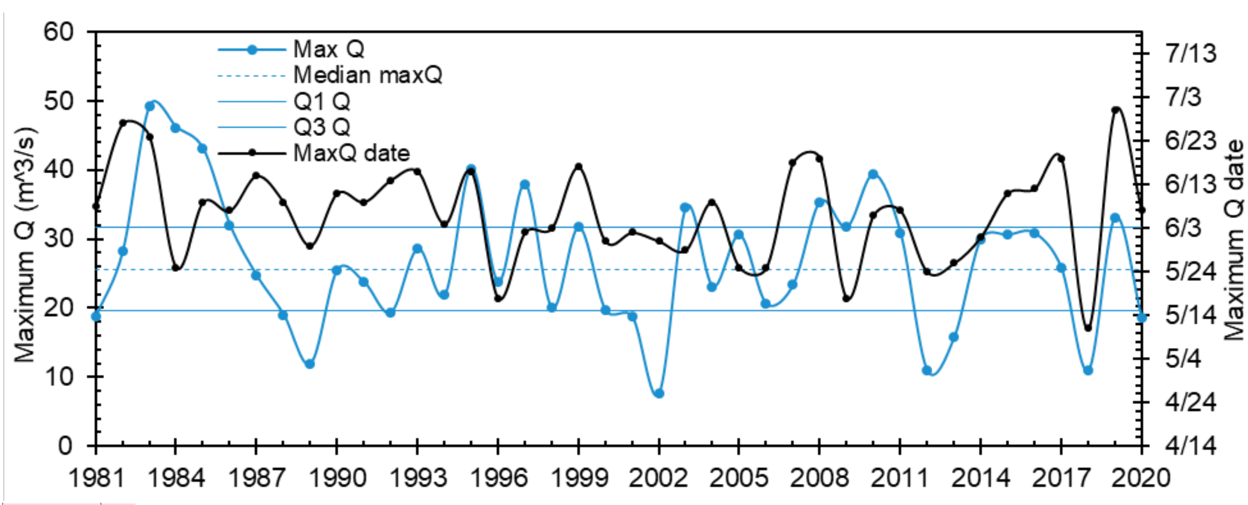


Figure 3[F8]. Peak streamflow and peak streamflow date for water years 1981-2020 in the Uncompahgre near Ridgway (USGS 09146200)

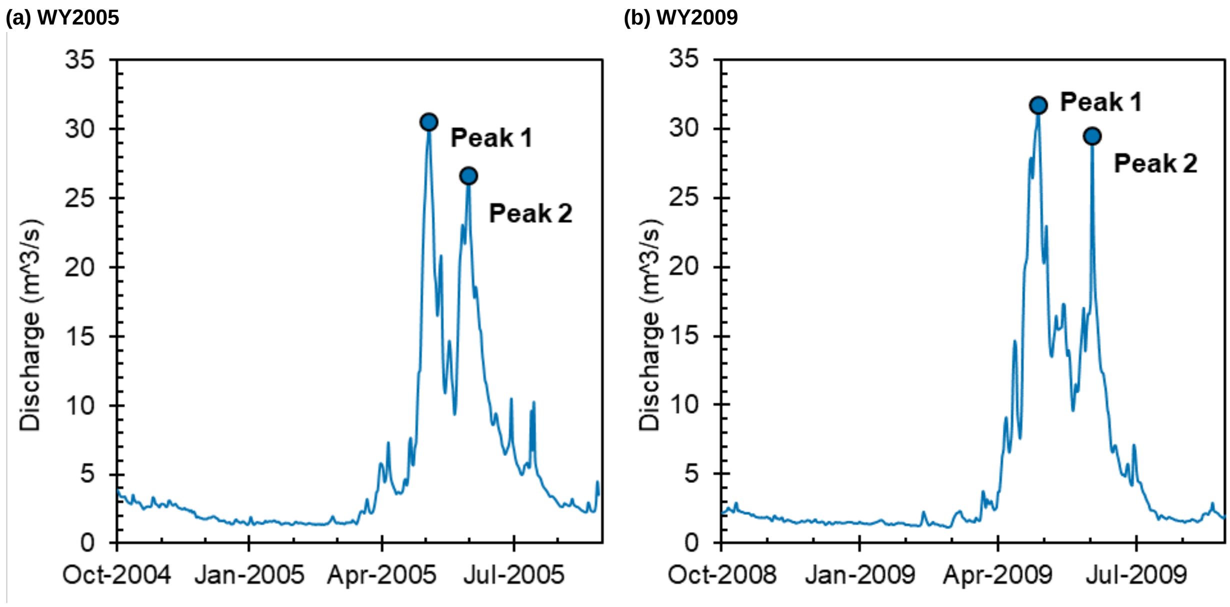


Figure 4. Hydrographs for USGS station 09146200 for water years 2005 and 2009 representing ~~good~~ distinct examples of double peak behavior in the Uncompahgre River near Ridgway, CO.

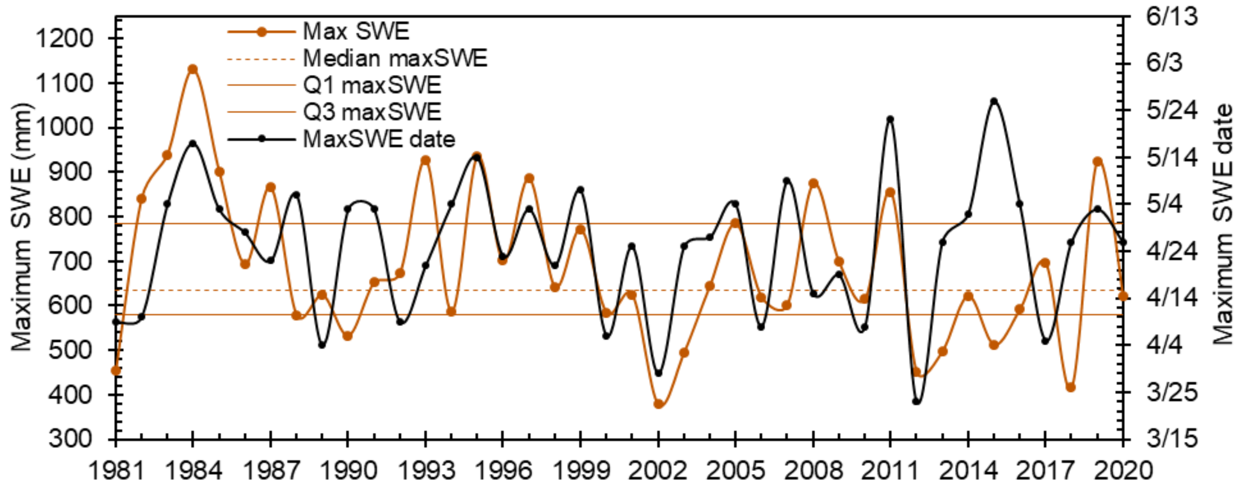


Figure 5[F9]. Maximum snow water equivalent (SWE) and maximum SWE date for water years 1981-2020 at Red Mountain Pass SNOTEL station (site id 713)

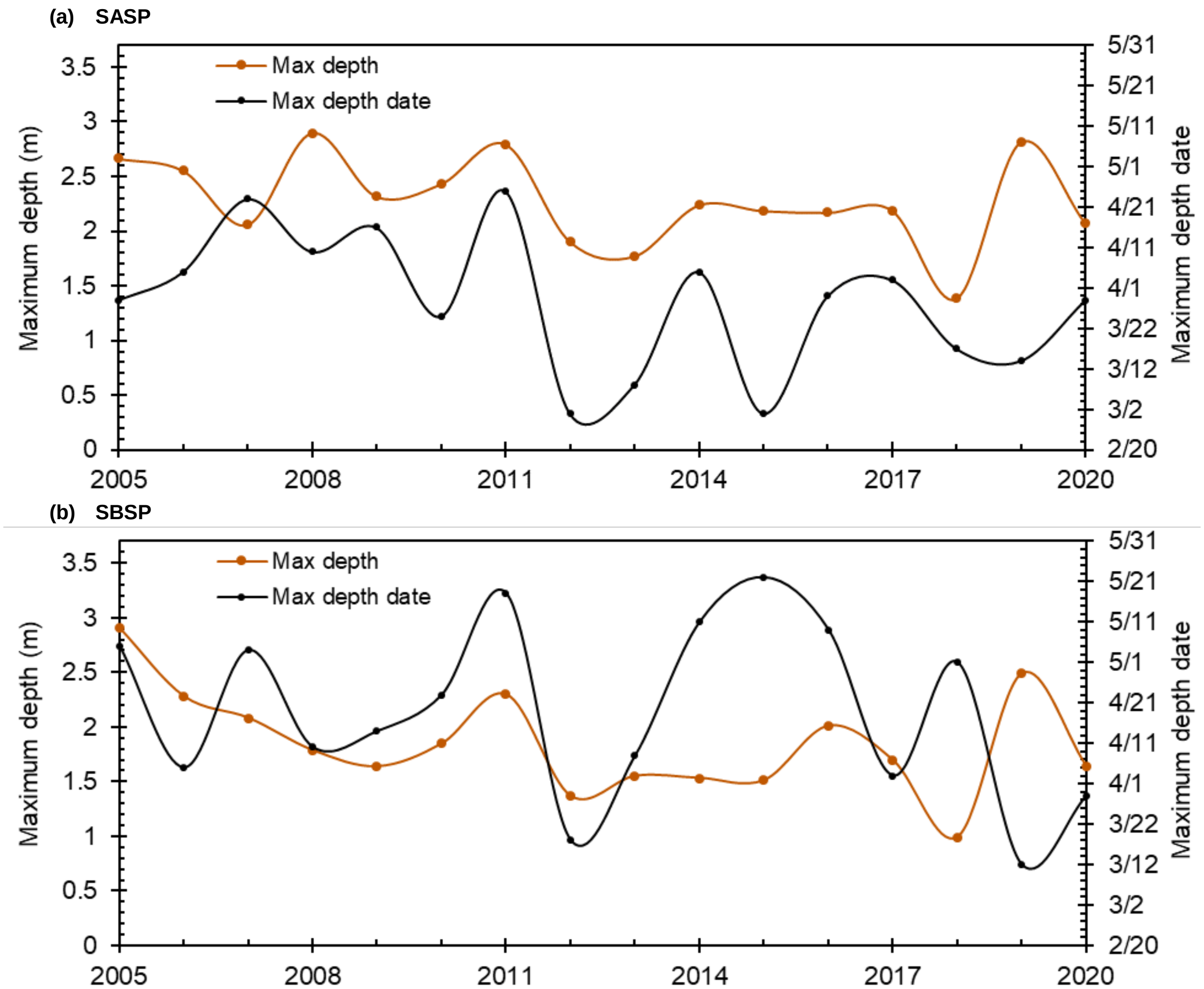


Figure 6[F10]. Maximum depth and maximum depth date for the period of record (WY2005-WY2020) at Colorado Snow and Avalanche Studies Swamp Angel Study Plot (top) and Senator Beck Study Plot (bottom). Data obtained from <www.snowstudies.org>

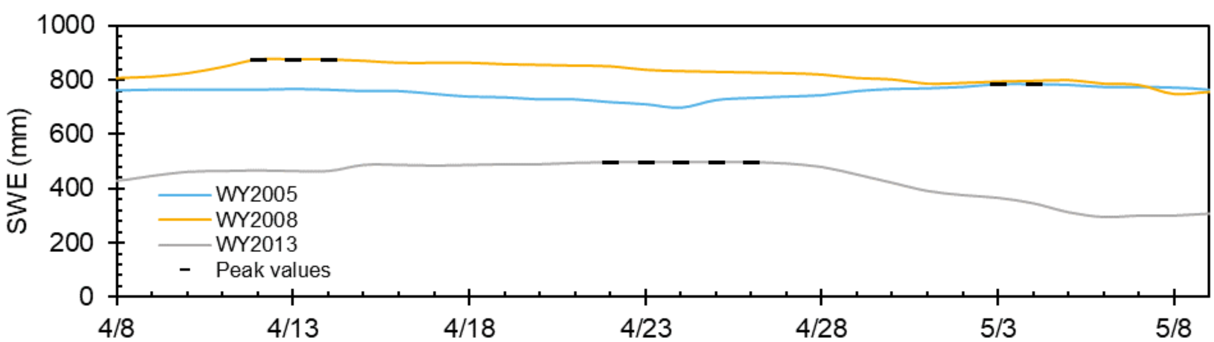


Figure 7. Peak SWE duration for WY2005 (2 days), WY2008 (3 days), and WY2013 (5 days) at Red Mountain Pass SNOTEL

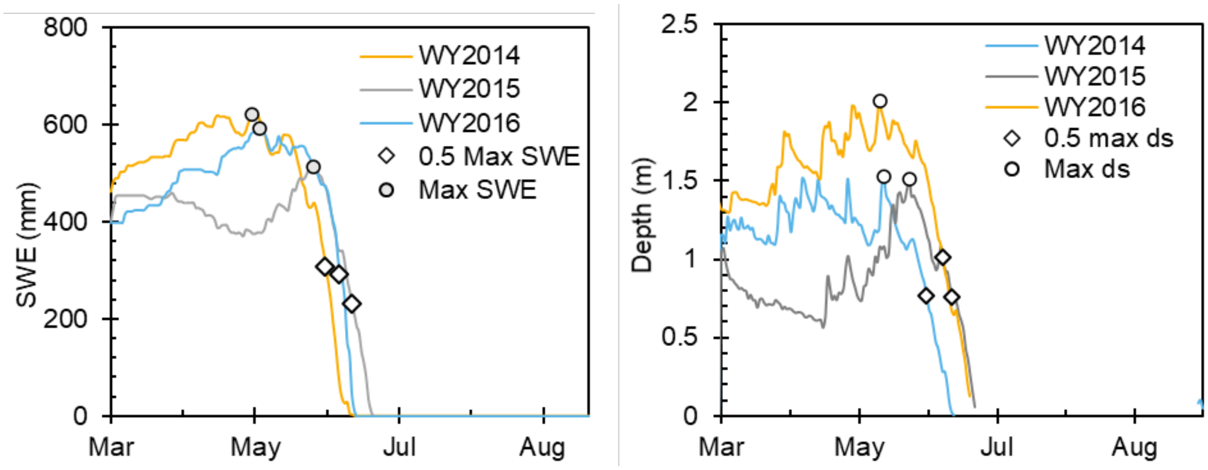


Figure 8. Snow water equivalent at Red Mountain Pass SNOTEL site 713 (RMP) and snow depth at Senator Beck Study Plot (SBSP) for waters years 2014, 2015, and 2016 justifying use of date of 80%[F11] maximum SWE and date of 50% maximum depth as markers of melt.

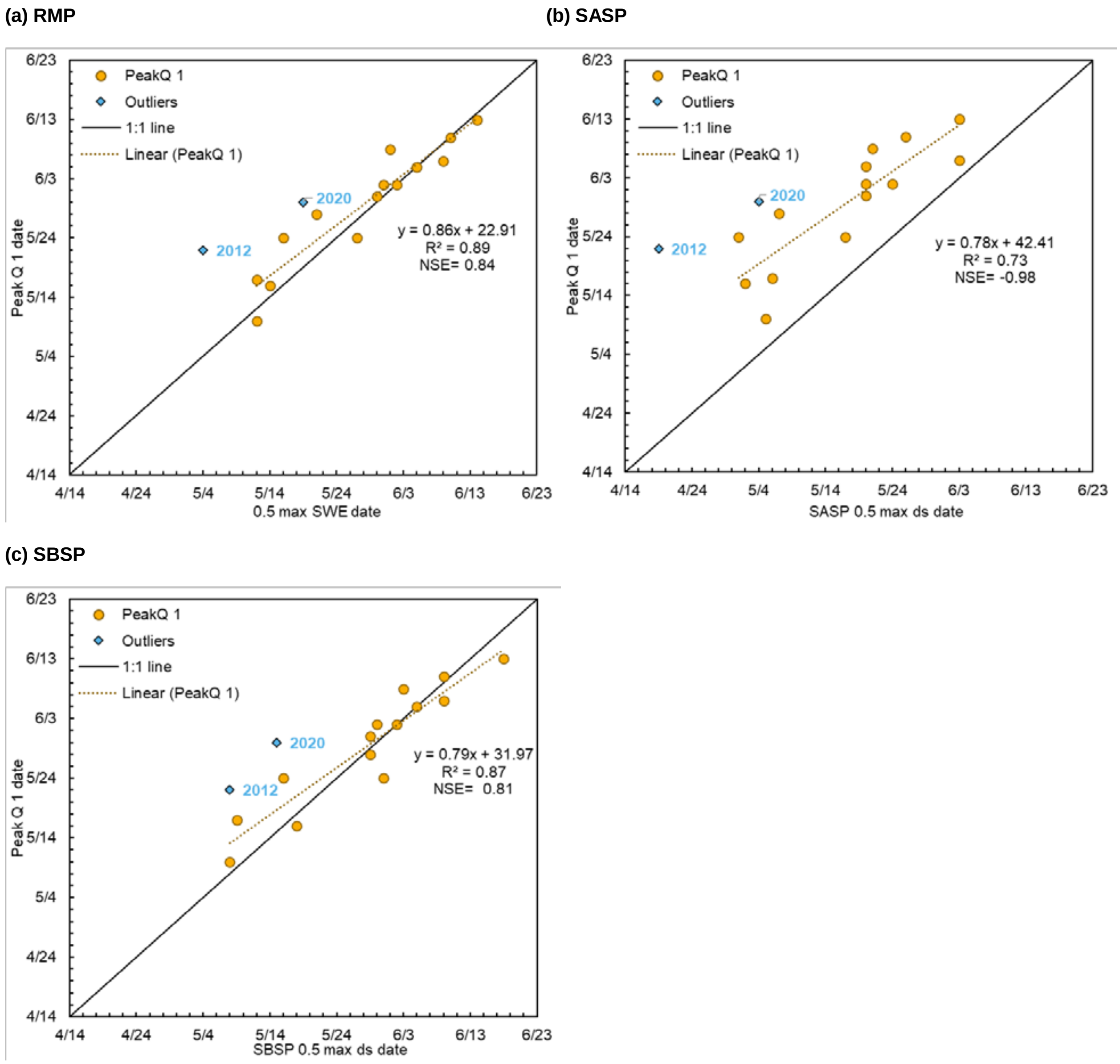


Figure 9. Correlation between (a) 50% maximum SWE at Red Mountain Pass SNOTEL station 713 (RMP), (b) 50% maximum depth at Swamp Angel Study Plot (SASP), and (c) 50% maximum depth at Senator Beck Study Plot (SBSP) and the first peak flow event to occur in the Uncompahgre River near Ridgway, CO (USGS 09146200). Years 2012 and 2020 omitted from reported R^2 and NSE values.

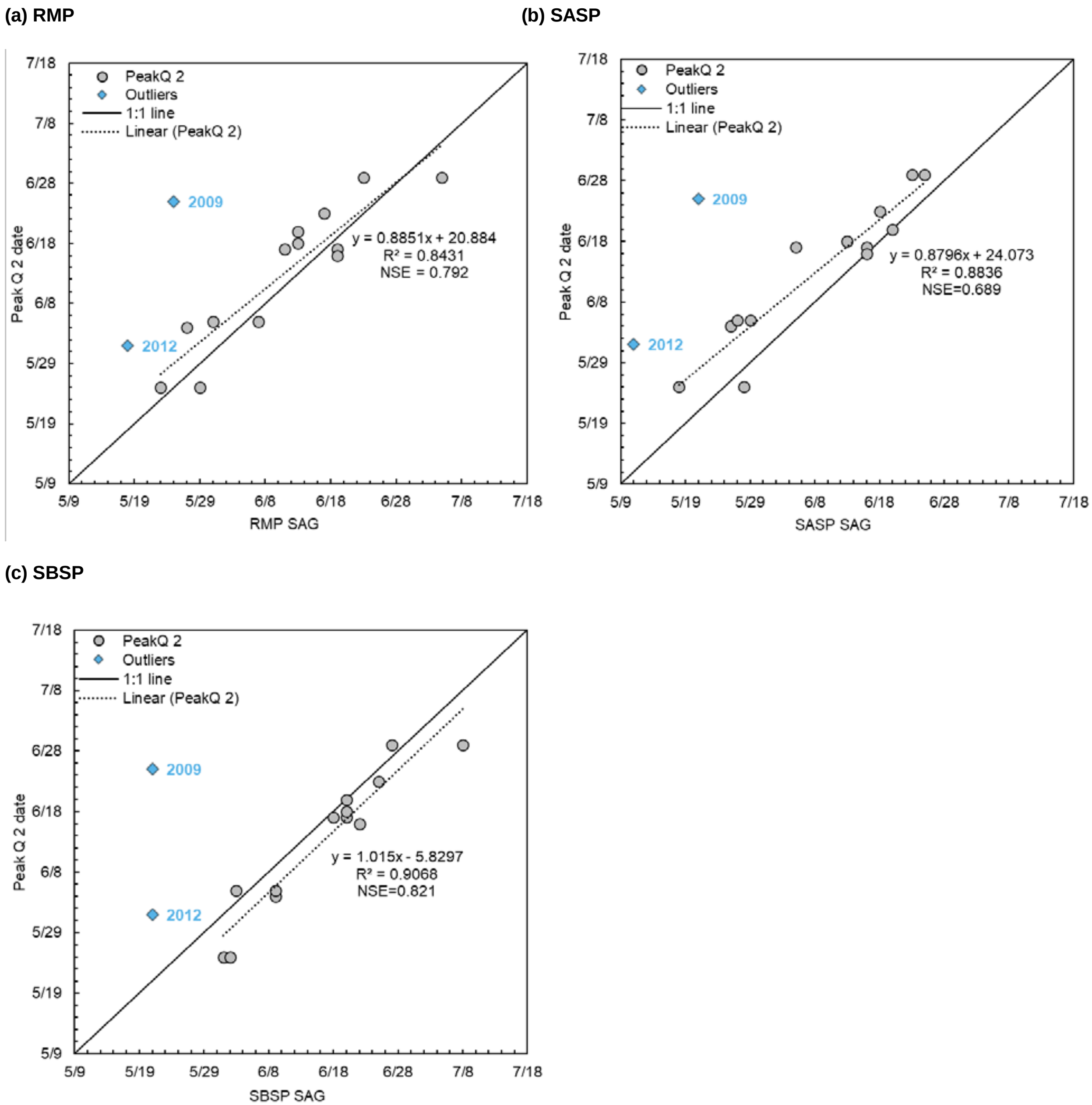


Figure 10. Correlation between snow all gone (SAG) at (a) Red Mountain Pass SNOTEL station 713 (RMP), (b) Swamp Angel Study Plot (SASP), and (c) Senator Beck Study Plot (SBSP) and the second peak flow event to occur in the Uncompahgre River near Ridgway, CO (USGS 09146200). Years 2009 and 2012 omitted from reported R^2 and NSE values.

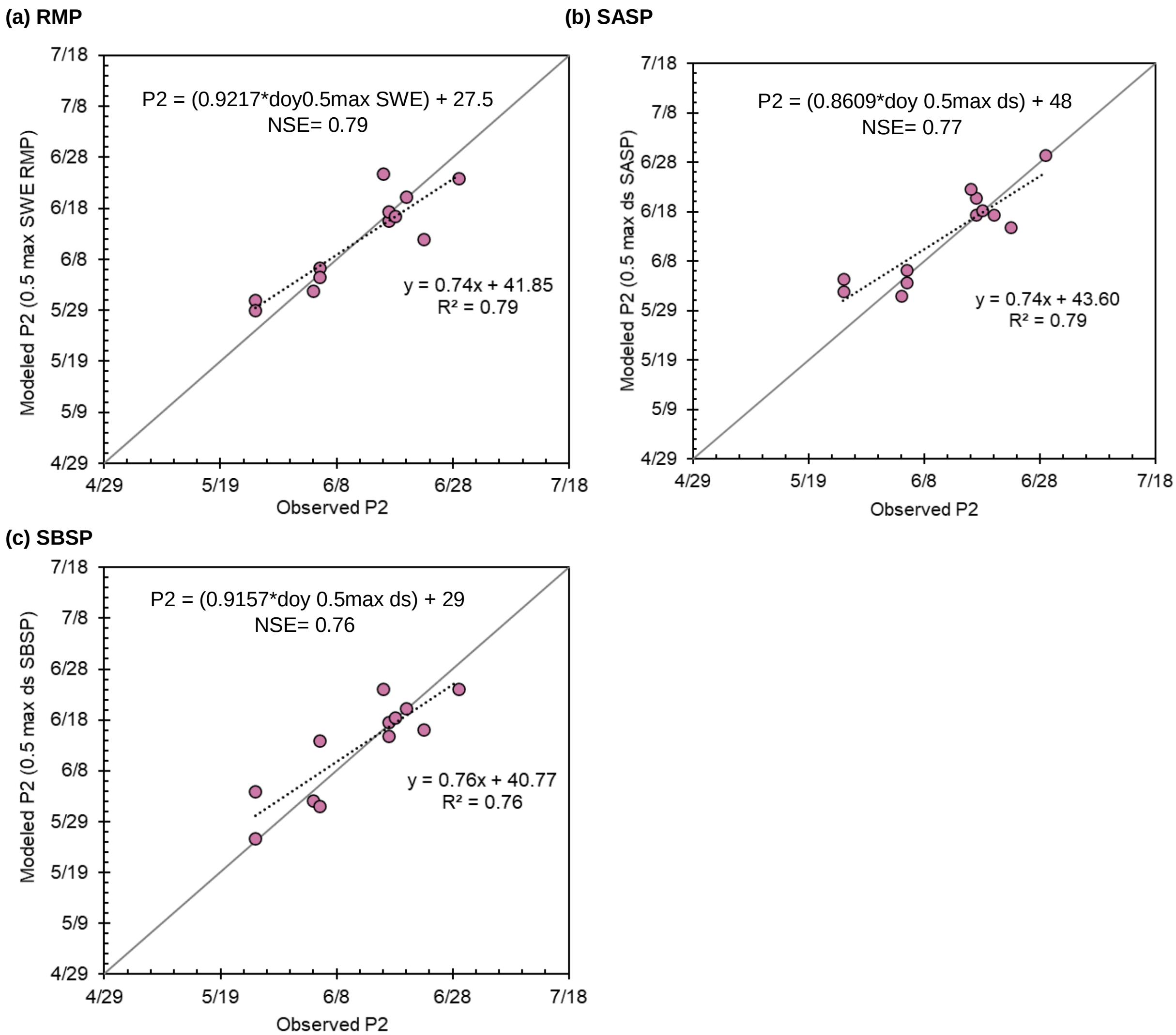


Figure 11. Modeled peak 2 occurrence in the Uncompahgre near Ridgway using (a) 50% depth[K12][F13] date at Red Mountain Pass SNOTEL (RMP), (b) 50% depth at Swamp Angel Study Plot (SASP) and (c) 50% depth at Senator Beck Study Plot (SBSP). Both the model equation/ NSE model fit and linear regression equation/R^2 information are presented. [LD14][F15]

Appendix

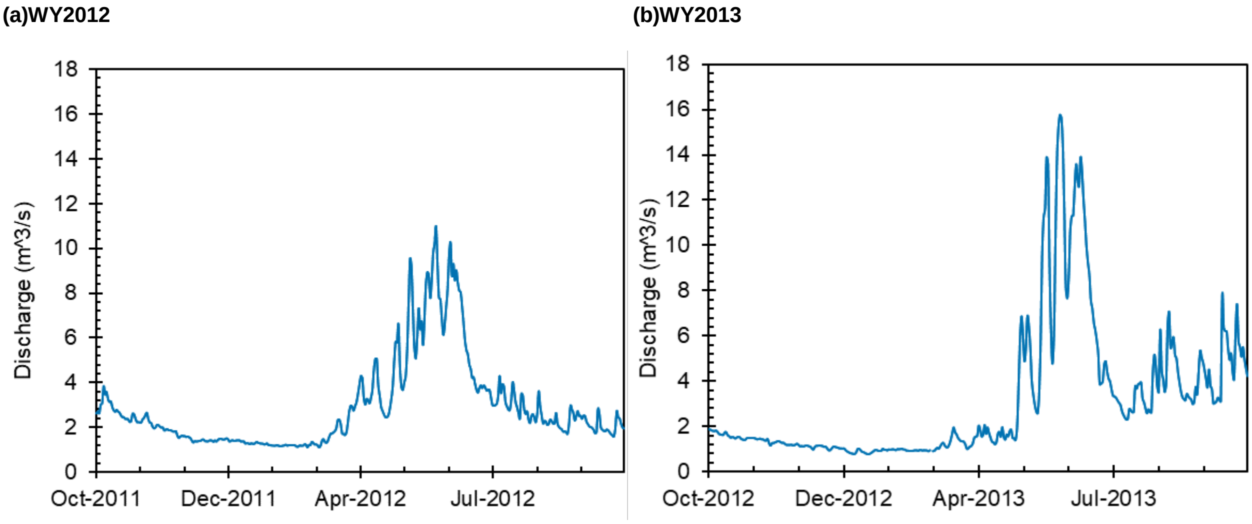
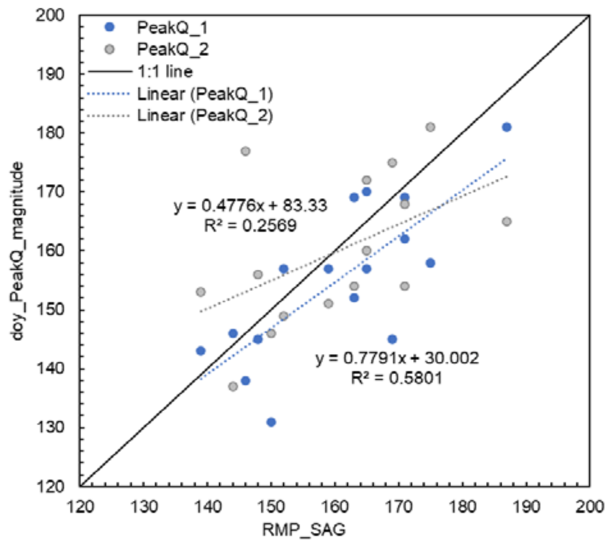
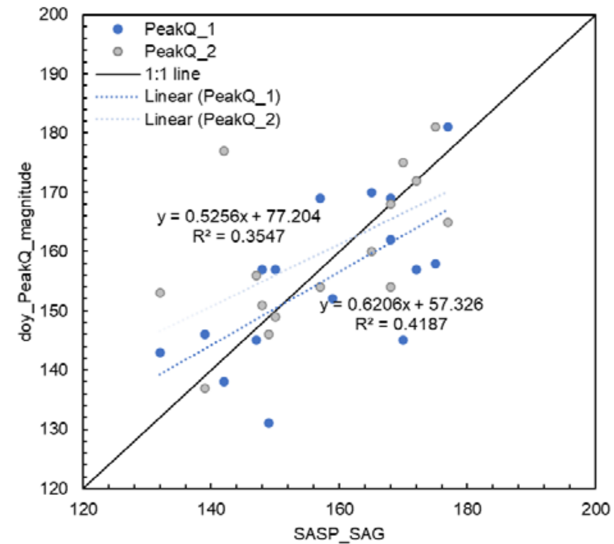


Figure A-1. Hydrographs for USGS station 09146200 and SWE for SNOTEL station 713 for water years 2012 and 2013 exhibiting at least three distinct peak discharge events in the Uncompahgre River near Ridgway.

(a) RMP



(b) SASP



(c) SBSP

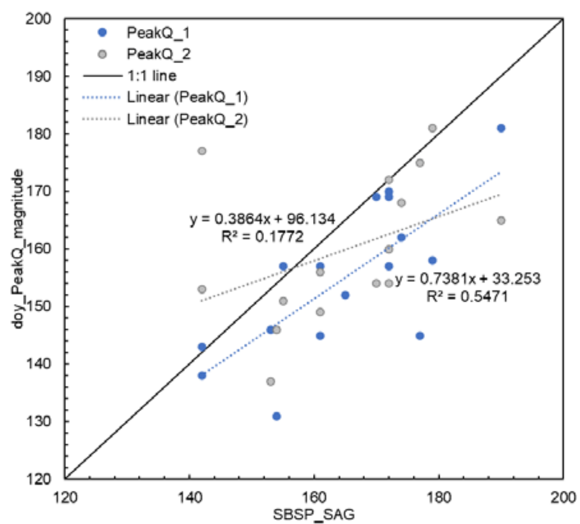
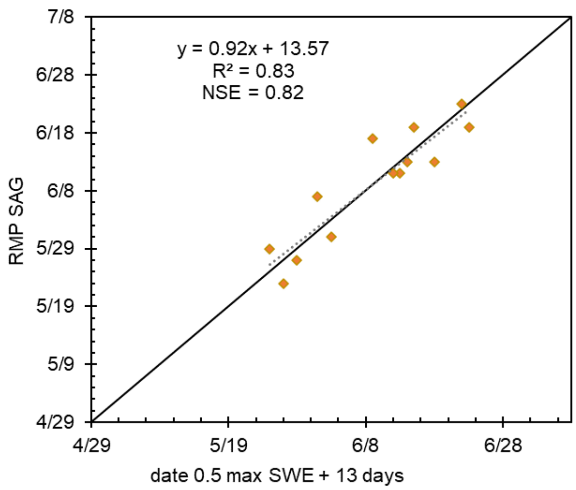
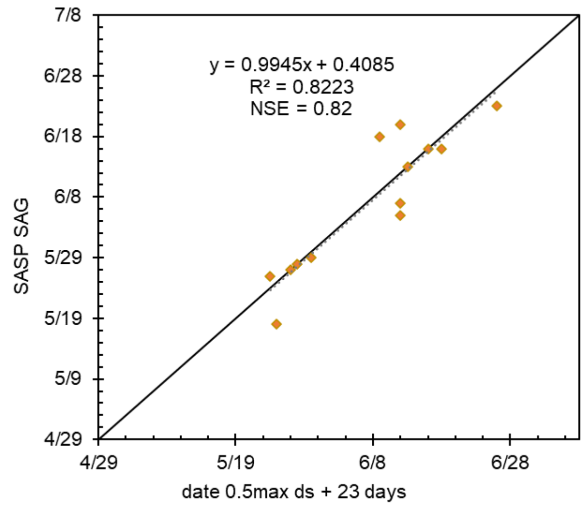


Figure A-2. Correlation between snow all gone (SAG) at (a) Red Mountain Pass SNOTEL station 713 (RMP), (b) Swamp Angel Study Plot (SASP), and (c) Senator Beck Study Plot (SBSP) and diurnal peak flow events organized by discharge value (m^3/s) in the Uncompahgre River near Ridgway, CO (USGS 09146200).

(a) RMP



(b) SASP



(c) SBSP

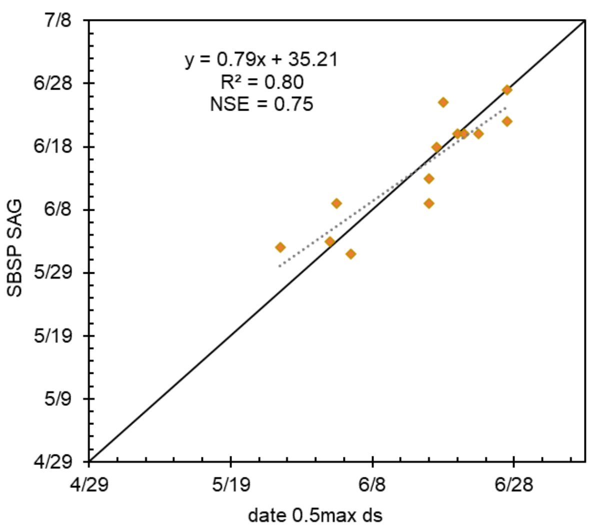


Figure A-3. Correlations between (a) modified 50% SWE date and RMP SAG, (b) modified 50% depth date and Swamp Angel Study Plot SAG and (c) 50% depth date at Senator Beck Study Plot (SBSP)

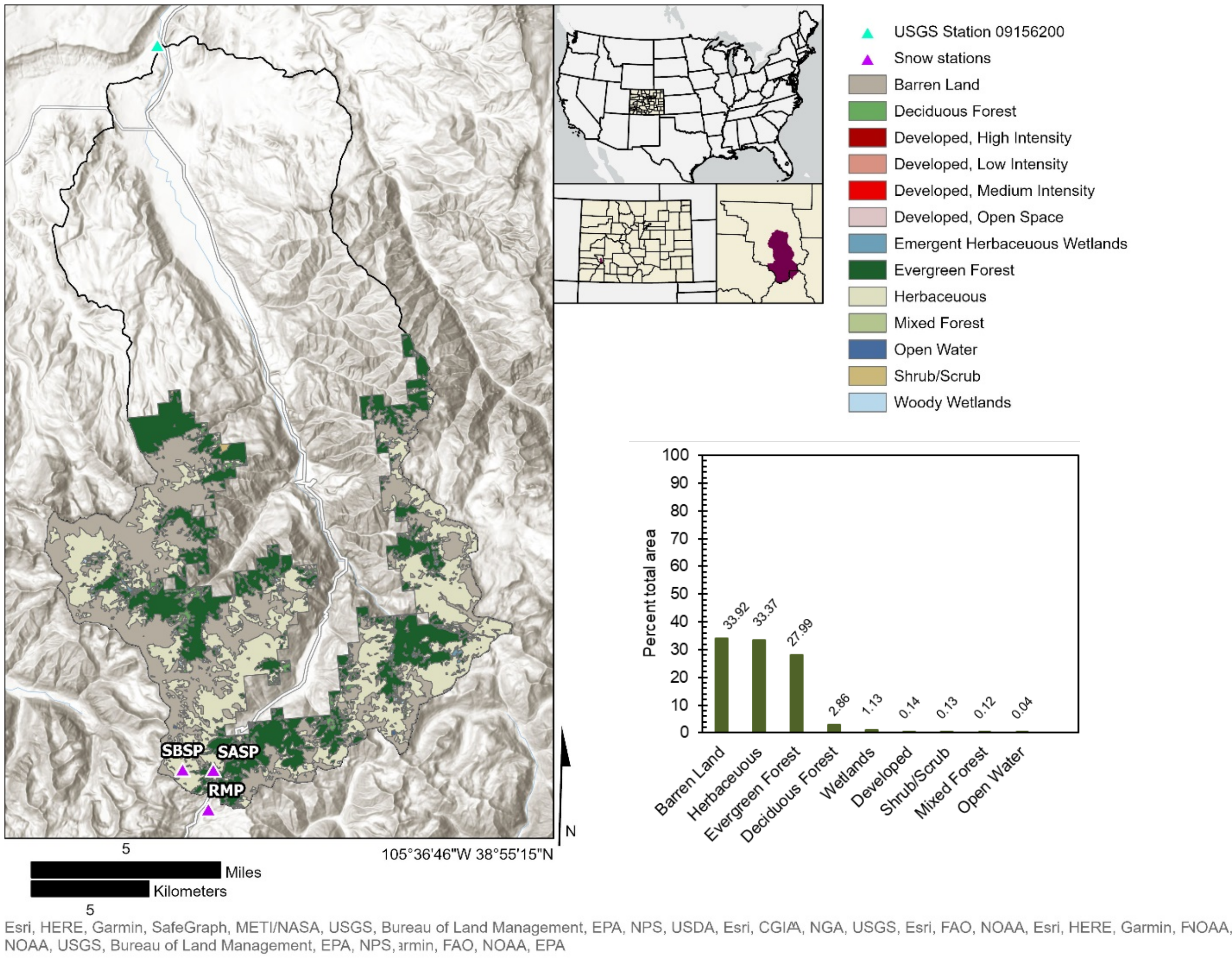


Figure A-4[F16]. Landcover types in the persistent snow zone[F17] of the upper Uncompahgre River watershed in southwestern Colorado. Data originally from the National Landcover Dataset and Mountain Scholar <http://hdl.handle.net/10217/171907>.

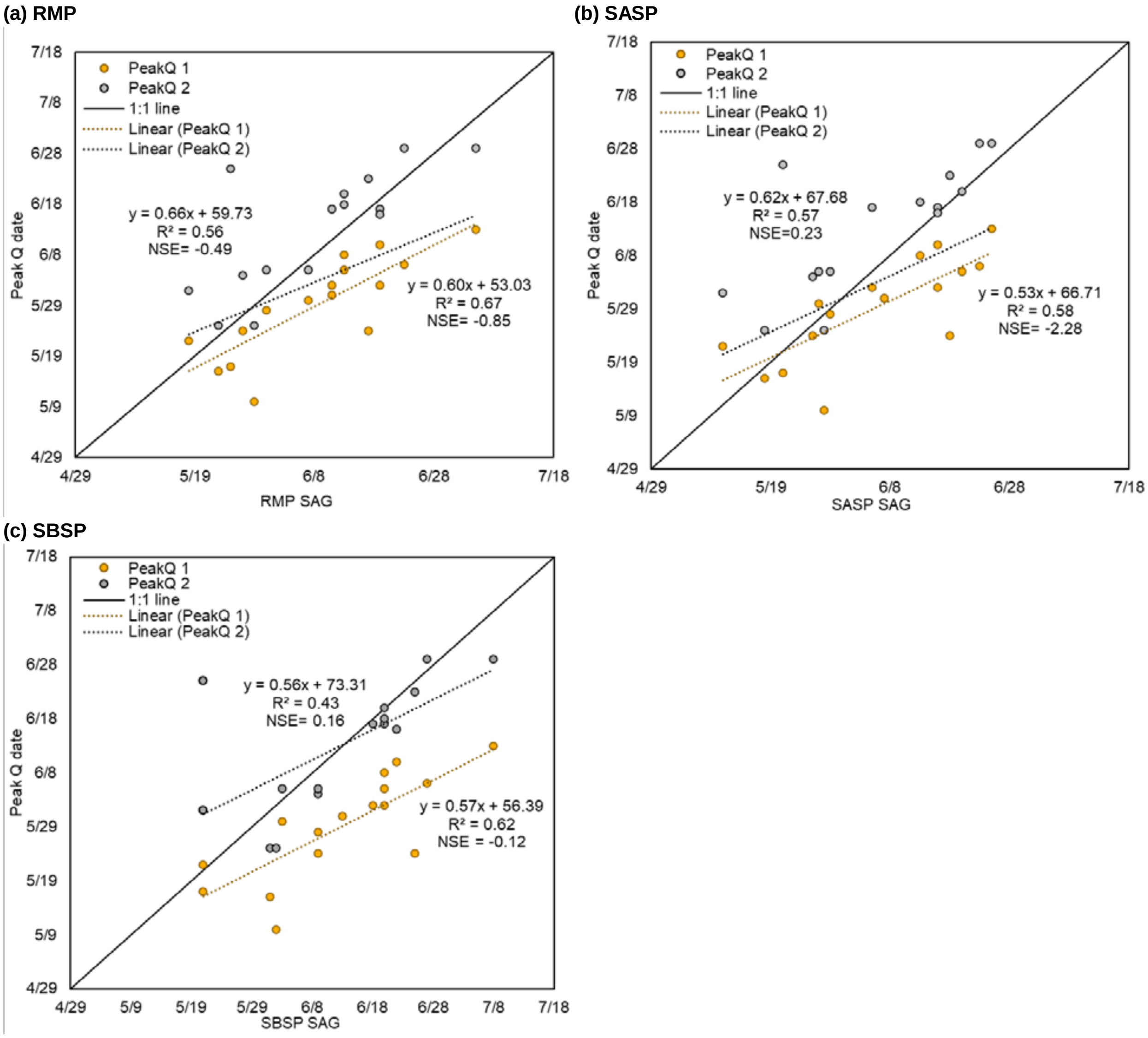


Figure A-5. Correlation between snow all gone (SAG) at (a) Red Mountain Pass SNOTEL station (RMP), (b) Swamp Angel Study Plot (SASP), and (c) Senator Beck Study Plot (SBSP) and the two flow events in the Uncompahgre River near Ridgway.

Correlation coefficients were similar across all six scenarios involving snow all gone date (RMP SAG: peak 1 date, RMP SAG: peak 2 date, SASP SAG: peak 1 date, SASP SAG: peak 2 date, SBSP SAG: peak 1 date, and SBSP SAG: peak 2 date) and model efficiency measured by the NSE was low (NSE<0.3) (Table 3). However, visual inspection of data spread, linear regression slopes, and 1:1 line fit suggested that the second peak streamflow event date (peak 2) correlated better with snow all gone dates across all stations than the first peak streamflow event date (peak 1) and that model fit may be impacted by outlier years (Figure A-5). Regression slopes were nearer to 1 (indicating a better "modeled" fit) and data spread appeared less dispersed and clustered closer to the 1:1 line than peak 1 (also indicating better "modeled" fit).

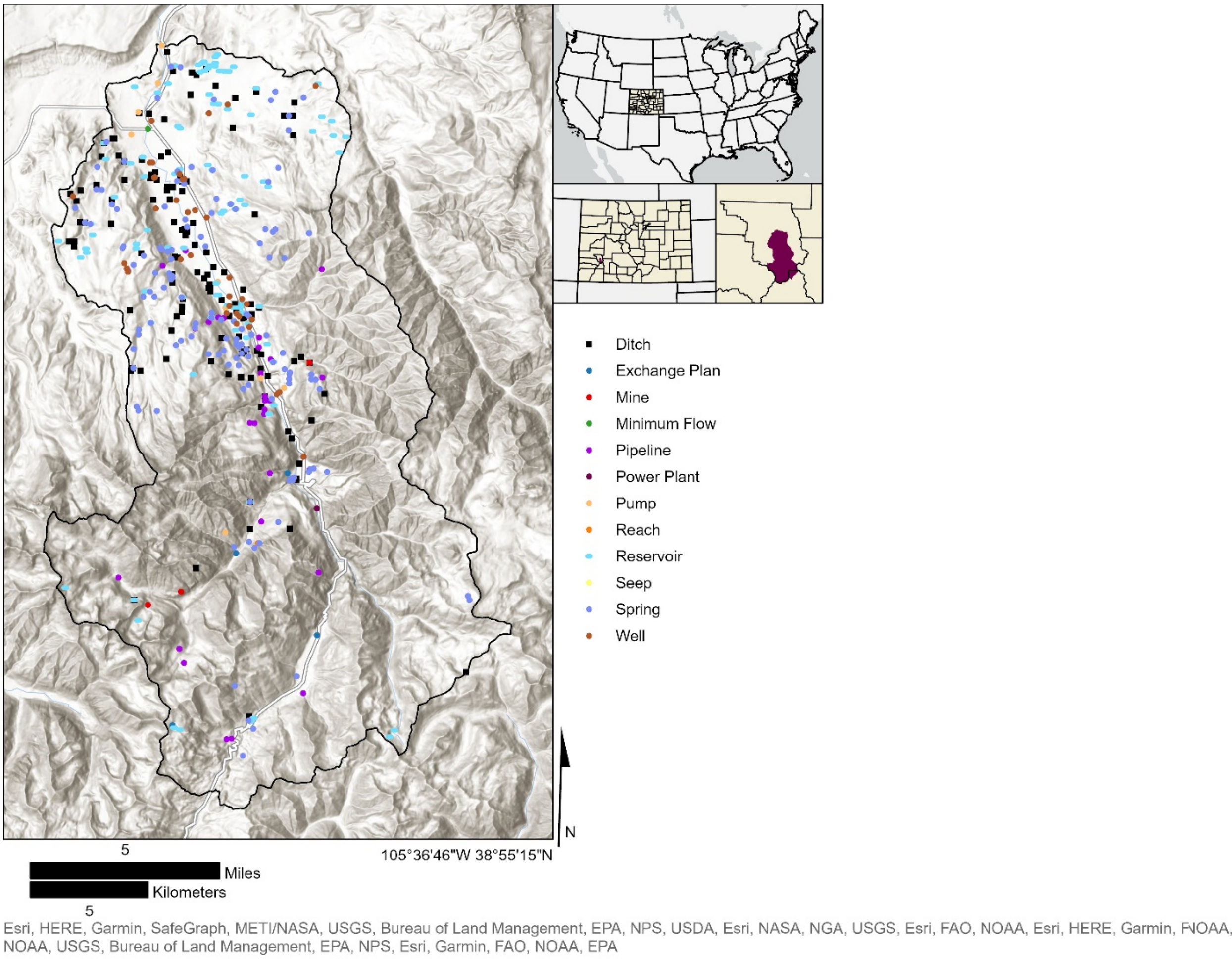


Figure A-6. Water rights claims in the upper Uncompahgre River watershed in southwestern Colorado. Data originally from the Colorado Division of Water Resources.