Exploring the Applicability of Radar-Based Quantitative Precipitation Estimates for Emergency Assessment of Post-Wildfire Debris Flow Hazards in Colorado

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Introduction

Debris flows in a post-wildfire landscape are often initiated by short duration, high intensity rainfall (Canon et al. 2008). The U. S. Geological Survey relies on in-situ rain gauges co-located with debris flow events to characterize rainfall triggering conditions (Staley et al. 2017). However, spatial coverage of rain gauges lack continuity and gauges are often scarce or nonexistent, especially in mountainous regions where they are difficult to install and maintain. Furthermore, mountains can provoke complex and heterogeneous precipitation patterns drastically limiting the spatial range of gauge accuracy (Lundquist et al. 2019). Several remotely sensed products provide gridded estimates of precipitation that could improve the spatial and temporal estimation of rainfall which initiates post-wildfire debris flows (Moody et al. 2013). If gridded precipitation products are adequate, they can be used to improve rainfall thresholds, and to understand debris flow initiation in areas with sparse gauge coverage or no gauges.

The purpose of this study is to explore the potential for high resolution Quantitative Precipitation Estimates (QPEs) to assess debris flow producing rainfall. Specifically, we use Multi-Radar Multi-Sensor (MRMS), a radar-based product corrected by multiple remote and in-situ sensors. Precipitation estimates from radar have been used for improving early warning of debris flows (NOAA–USGS Task Force 2005; Jorgensen et al. 2011; Li et al. 2022). However, radar QPEs have not been used for the assessment of intensity thresholds as radar observations are subject to several sources of uncertainty in mountains, including variability of precipitation at radar beam altitude versus ground level and beam blockage by terrain (Berne and Krajewski 2013). Several studies have evaluated the performance of MRMS and similar multi-sensor QPEs in mountainous regions (Moreno et al. 2012; Henn et al. 2018; Bytheway et al. 2019). There is still a lack of evaluation of the uncertainty at hourly and sub-hourly resolutions, which is required for debris flow analysis (Bytheway et al. 2020).

In this study we compare the rainfall intensity and accumulation of MRMS at several gauge locations in two burn areas in Colorado. The results show that MRMS can align remarkably well with gauge sub-hourly precipitation, but often misses the magnitude or timing of the rainfall intensity. The MRMS precipitation estimates are mapped for both study areas throughout the duration of the storms to observe the spatial variability. The spatial heterogeneity of storm accumulation and intensity suggests a more limited spatial accuracy of rain gauges than is often assumed. These results illuminate the potential problems with using MRMS for hydrologic applications requiring high spatiotemporal resolution. Conversely the spatial variability of precipitation confirms the limitations of assuming constant gauge-based rainfall intensity across an area of interest.

Methods

The 2020 Colorado wildfire season was the largest in state history and was followed by several devastating post-wildfire debris flows the next year. This study looks at one storm event in the Cameron Peak burn area and two storm events in Grizzly Creek burn area which caused the most impactful debris flows (Kostelnik et al. 2021). MRMS was evaluated during the 20 July 2021 storm event in the Cameron Peak burn area and the 29 July 2021 and 31 July 2021 storm events in the Grizzly Creek burn area. These storms produced multiple debris flows in both burn areas (Figure 1). All basins in the Grizzly Creek burn area were considered for the 20 July storm, however only Blue Gulch was considered for the 31 July storm (Figure 1).

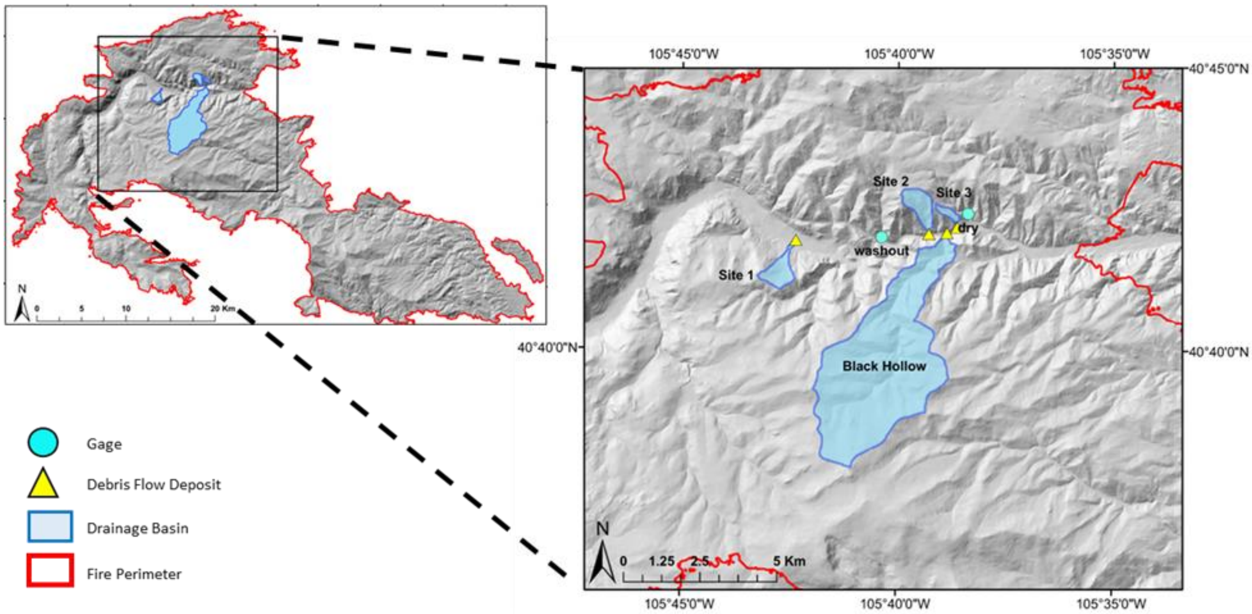
In the Cameron Peak study area three precipitation gauges were used to evaluate MRMS, including one disdrometer collocated with the Dry Creek tipping bucket (Figure 1). The Dry Creek tipping bucket time series was shifted by an hour to correct errors in the device clock. At Grizzly Creek, MRMS was evaluated using the four tipping bucket gauges closest to the debris flows, including gauges GCEC2, GCTC2, GCCC2, and GCDC2 (Figure 1).

The MRMS dataset provides a mosaic of QPEs for the contiguous United States with a spatial resolution of 1 km. These products are radar-based, with multi sensor corrections from local gauges, satellite data, atmospheric environmental data, and controls for orographic effects (Zhang et al. 2016). The radar-only 2-minute precipitation rate product was used to calculate the 15-minute intensity and storm total accumulation. A simple multiplicative correction factor, using the 1-hr multi-sensor QPE and 1-hr radar-only QPE, was applied to the 2-minute precipitation rate product to improve accuracy. Time series were converted to MST for comparison.

Performance metrics were calculated for the 15-minute intensity and storm total accumulation. For each gauge, MRMS data were taken from the radar product grid cell containing the gauge coordinates. The magnitude of the residuals of gauge vs. MRMS estimates were evaluated using root mean squared error (RMSE). The relative error was evaluated with the Nash-Sutcliffe Coefficient of Efficiency (NSE), which measures the squared error relative to the variability of the observations. The Pearson correlation coefficient (CC) was used to measure the strength of the relationship between the two measurements.

We then mapped the spatial distribution of 15-minute rainfall intensity as a function of duration above the 15-minute intensity threshold for 50 percent likelihood of debris flow occurrence derived from the USGS post-fire debris flow hazard assessment model (Kostelnik et al. 2021).

Cameron Peak Fire Study Area:



Grizzly Creek Fire Study Area:

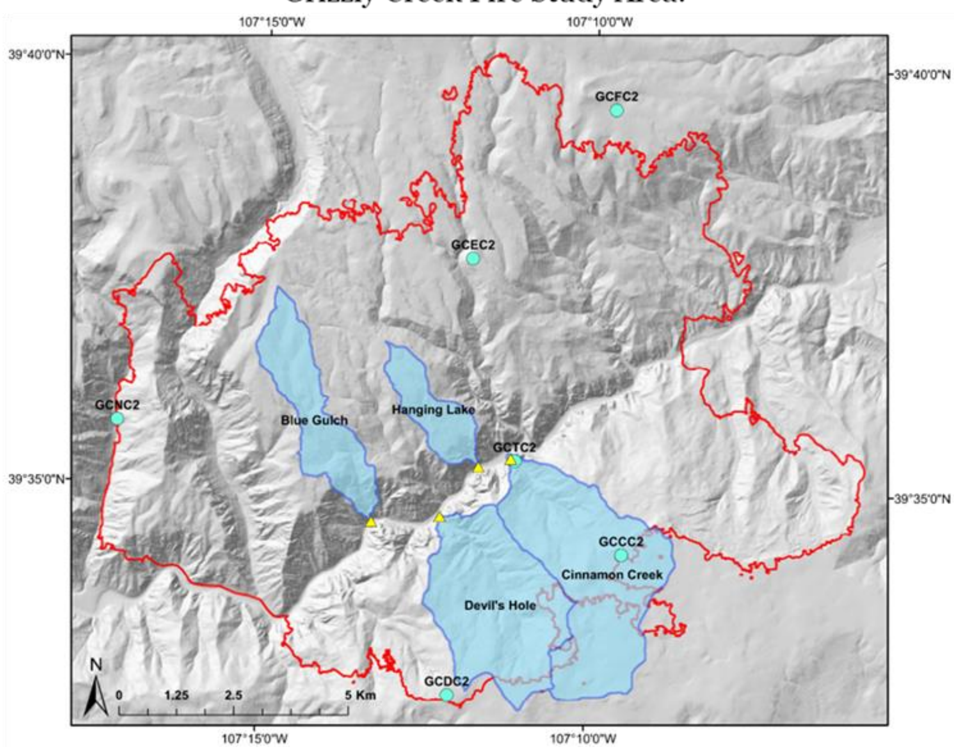


Figure 1. Study areas with fire perimeters and locations of gauges, drainage basins, and debris flow deposits.

Results and Discussion

The results from the Cameron Peak study area (Figure 2) show inconsistent performance of MRMS products in comparison to gauge data. Depending on the site, MRMS underpredicted or overpredicted intensity and total accumulation. However, the timing of the peaks matches well, and the intensity correlation coefficient is relatively good. Interestingly, the disdrometer measurement (Figure 2b) was significantly lower than the tipping bucket at Dry Creek (Figure 2a); the cause of this discrepancy is unknown.

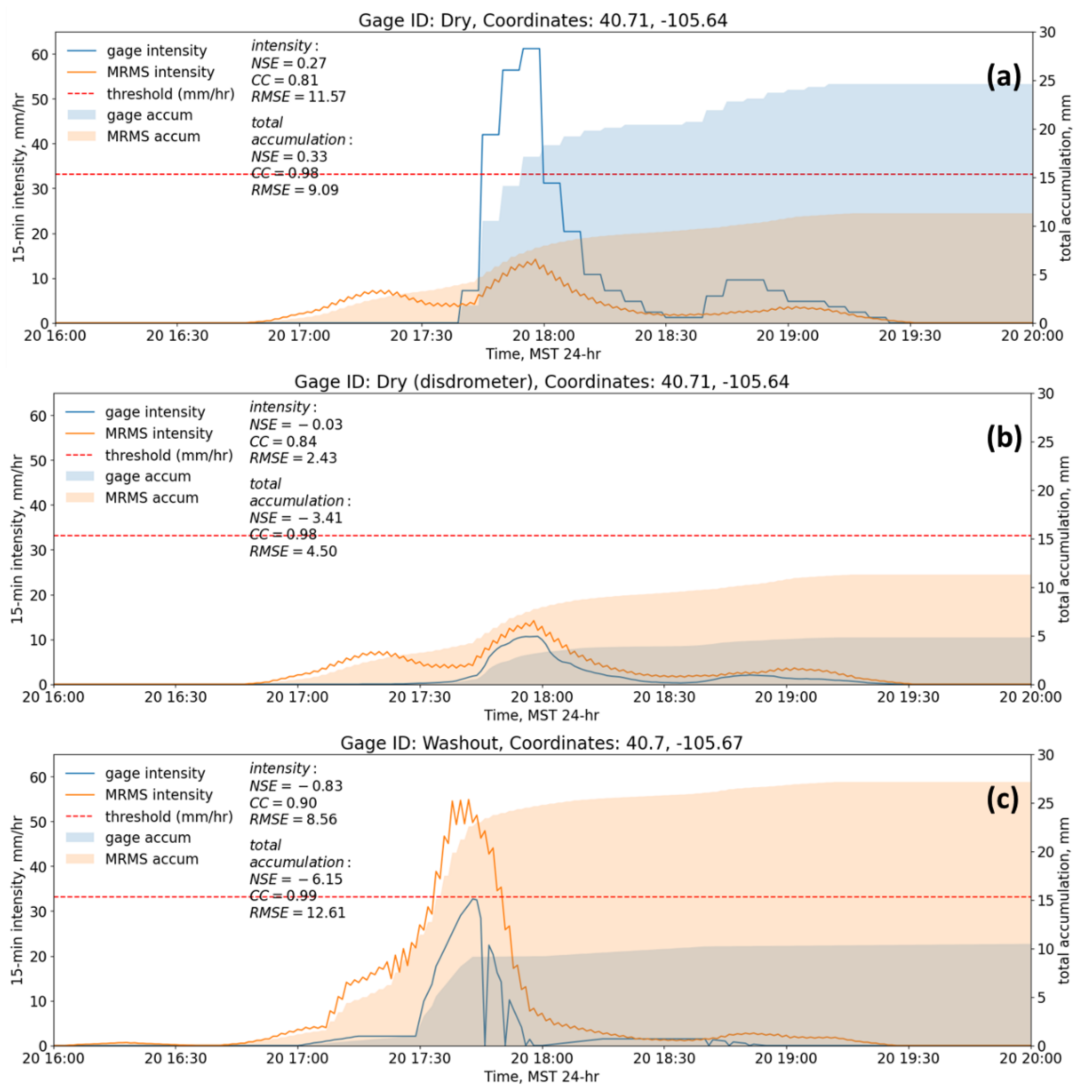


Figure 2. Time series comparison of MRMS and gauge 15-minute intensity and storm total accumulation with performance metrics for 20 July 2021 storm in Cameron Peak burn area. 15-minute intensity threshold for 50% likelihood of debris flow occurrence shown in dashed red line.

There were several optimal matches in the Grizzly Creek study area (Figures 3 and 4), based on the NSE and CC being close to 1.0 and the RMSE being relatively close to zero, including GCEC2 during the 29 July and 31 July storms (Figure 3a, Figure 4a), and GCCC2 and GCDC2 during the 29 July storm (Figure 3c, Figure 3d). MRMS missed the magnitude of the intensity at GCCC2

(Figure 4c), and the timing of MRMS was inaccurate at GCDC2 for the 31 July storm (Figure 4d). For both storms, gauge GCTC2 reported no precipitation while MRMS estimated significant intense rainfall (Figure 3b, Figure 4b).

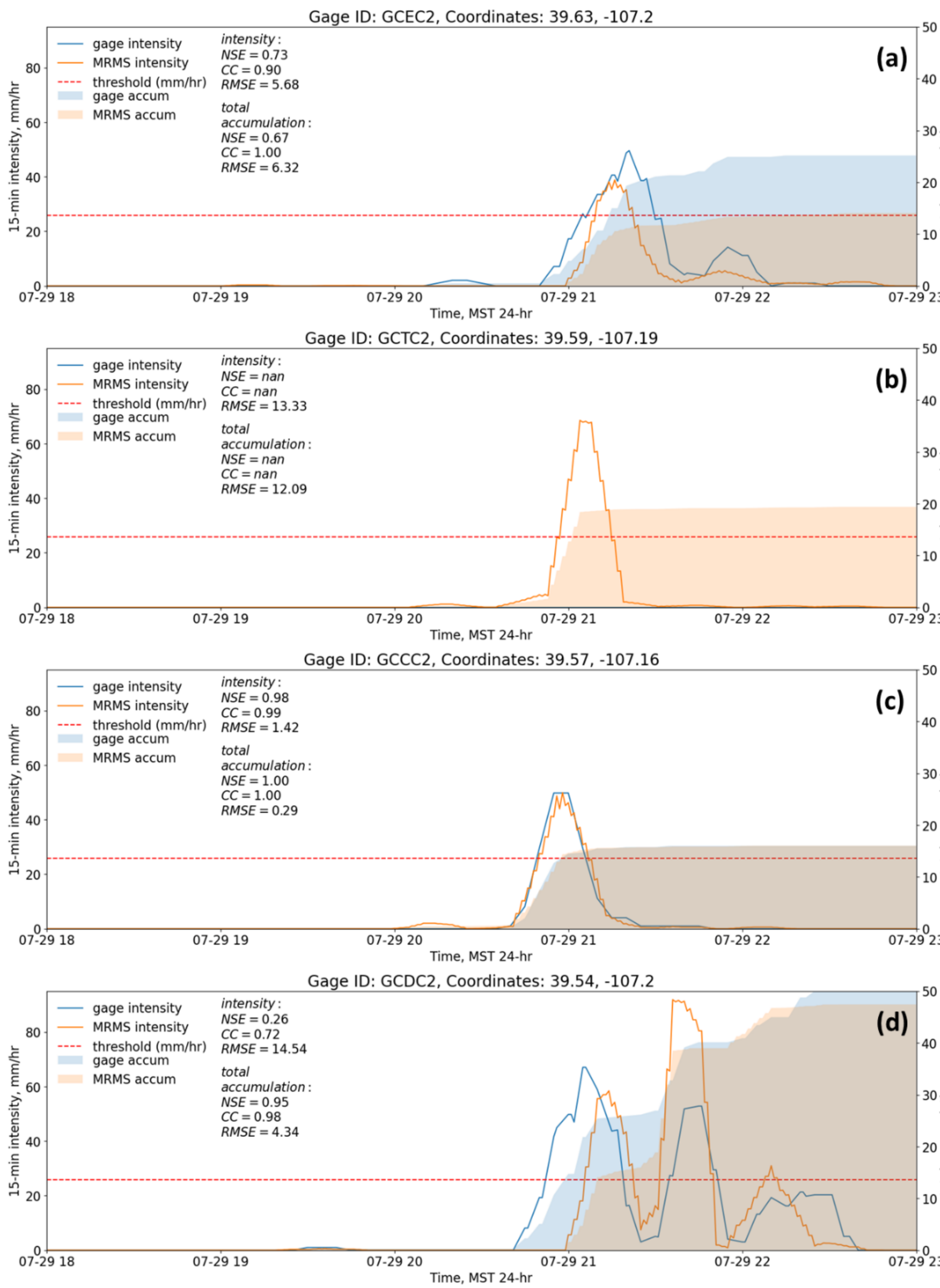


Figure 3. Time series comparison of MRMS and gauge 15-minute intensity and storm total accumulation with performance metrics for 29 July 2021 storm in Grizzly Creek burn area. 15-minute intensity threshold for 50% likelihood of debris flow occurrence shown in dashed red line.

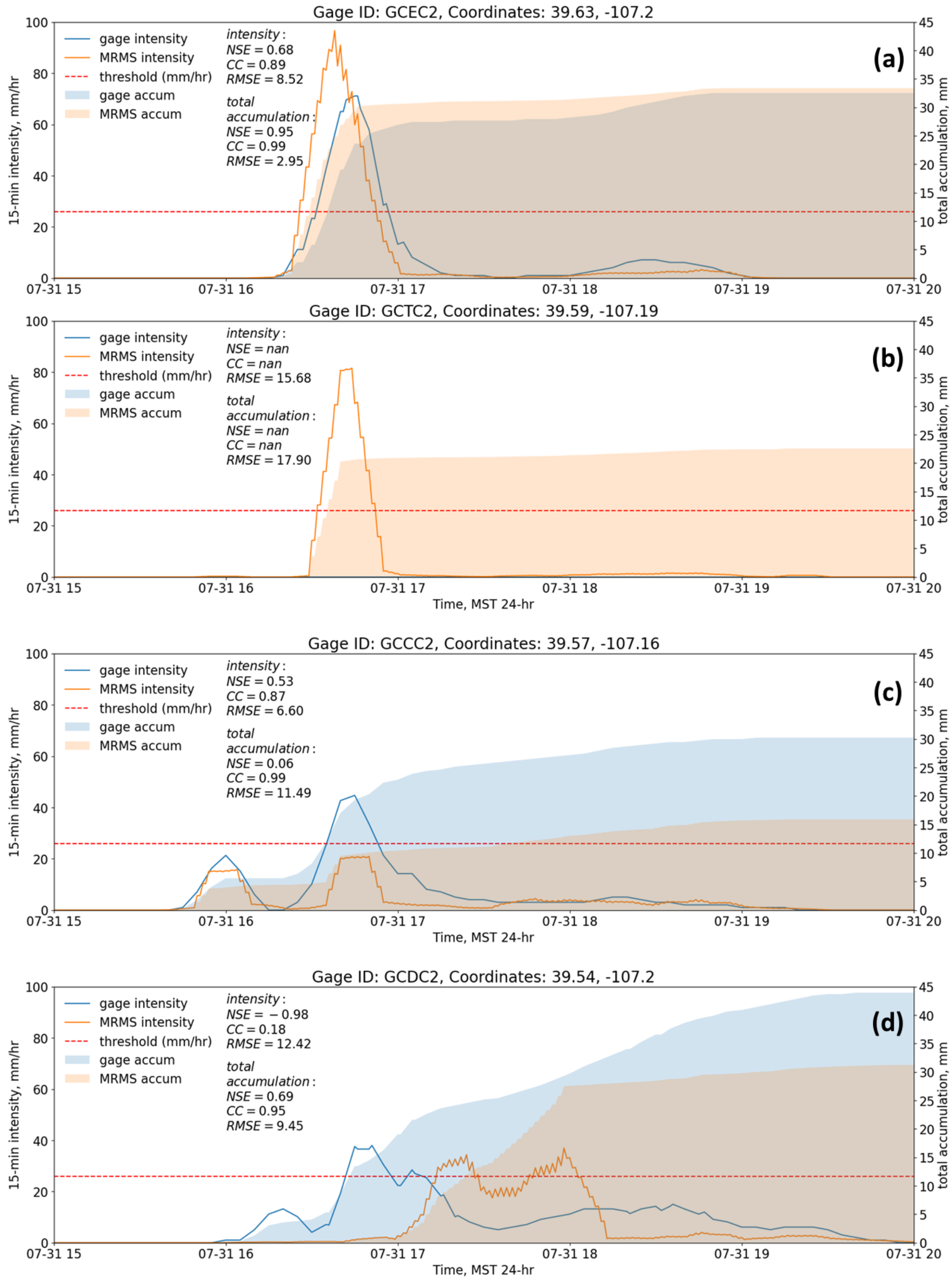


Figure 4. Time series comparison of MRMS and gauge 15-minute intensity and storm total accumulation with performance metrics for 31 July 2021 storm in Grizzly Creek burn area. 15-minute intensity threshold for 50% likelihood of debris flow occurrence shown in dashed red line.

The results of this study show that although MRMS can perform well, it's accuracy for sub-hourly applications should be verified with gauge measurements when possible. MRMS includes a Radar Quality Index (RQI) which provides an estimate of the uncertainty associated with terrain blockage, higher beam heights, and the beam position with respect to the freezing level (Zhang et al. 2011). An RQI of 1.0 suggests no uncertainty associated with these problems. RQI is set to 0.0 when blockage is less than 50 percent. The storms had relatively similar RQIs for all events. The 20 July mean RQI was 0.90, the 29 July mean RQI was 0.85, and the 31 July mean RQI was 0.82. This similarity, despite varying performance, suggests that RQI is not sufficient to determine usefulness of MRMS at this scale.

The spatial variability of precipitation (Figure 5) highlights the issues with using a sparse gauge network. Precipitation intensity is highly variable across the study area for the 20 July and 31 July events. The 31 July map also highlights the complexity of the erosional response as only a small portion of the Blue Gulch basin saw intense rainfall after already producing a large debris flow.

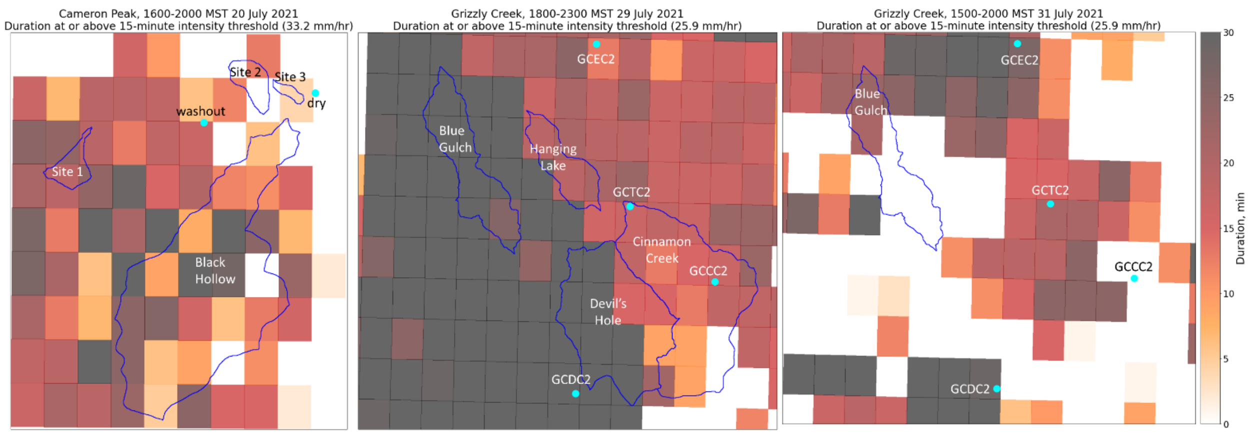


Figure 5. Heatmap showing duration (minutes) above 15-minute intensity threshold for 50% likelihood of debris flow occurrence shown in dashed red line for both study areas and all events.

Further evaluation of the gridded product revealed that the grid cell containing the rain gauge often performs worse than the eight nearest neighbor cells. This may be due to advection of hydrometeors as they fall from observation height to the ground, which is a large source of error during severe storms and is not corrected in the multi-sensor products (Zhang et al. 2016). Correcting this error may be an important step for using MRMS in this type of application, and several studies have developed approaches to correct this error (Seo and Krajewski 2015).

The results of this study do not conclusively show whether MRMS is suitable for applications requiring precipitation estimates with high spatial and temporal resolution. Instead, the results highlight issues with MRMS, possible improvements, and problems with sparse gauge networks. For regions with adequate gauge coverage, accuracy can be improved in radar-based products with various gauge correction methods (Ochoa-Rodriguez et al. 2019; Chiang and Chang 2009)

Conclusions

15-minute precipitation intensity and total storm accumulation were calculated from the MRMS 2-minute precipitation rate with a multi-sensor correction and evaluated against several gauges in two distinct burn areas during storm events with recorded debris flows. The purpose of this approach was to highlight challenges with radar-based products and sparse gauge networks for evaluation of precipitation thresholds for debris flows. The need for high-resolution precipitation data is more important than ever as mountain forests are burning more frequently (Higuera et al. 2021) and extreme precipitation is happening more often (Touma et al. 2022). High-resolution precipitation data in the mountains is important for many hydrologic applications, such as flood forecasting and water resource management.

This abstract is part of a larger study classifying sub-hourly precipitation estimates from the MRMS dataset throughout Colorado using gauges and identification of features in observations with varying performance. The goal is to provide a prediction of the performance of MRMS where no gauges exist that would be useful for hydrologic applications discussed in this extended abstract.

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