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Data Descriptor

Quality Control Impacts on Total Precipitation Gauge Records for Montane Valley and Ridge Sites in SW Alberta, Canada

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Abstract: AbstractThis paper presents adjustment routines for Geonor totalizing precipitation gauge data collected from the headwaters of the Oldman River, within the southwestern Alberta Canadian Rockies. The gauges are situated at mountain valley and alpine ridge locations with varying degrees of canopy cover. These data are prone to sensor noise and environment-induced measurement errors requiring an ordered set of quality control (QC) corrections using nearby weather station data. Sensor noise at valley sites with single-vibrating wire gauges accounted for the removal of 5% to 8% (49–76 mm) of annual precipitation. This was compensated for by an increase of 6% to 8% (50–76 mm) from under-catch. A three-wire ridge gauge did not experience significant sensor noise; however, the under-catch of snow resulted in 42% to 52% (784–1342 mm) increased precipitation. When all QC corrections were applied, the annual cumulative precipitation at the ridge demonstrated increases of 39% to 49% (731–1269 mm), while the valley gauge adjustments were −4% to 1% (−39 mm to 13 mm). Public sector totalizing precipitation gauge records often undergo minimal QC. Care must be exercised to check the corrections applied to such records when used to estimate watershed water balance or precipitation orographic enhancement. Systematic errors at open high-elevation sites may exceed nearby valley or forest sites.

Dataset: https://doi.org/10.20383/102.0551

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Keywords: precipitation; totalizing precipitation gauge; Geonor; time-series adjustment; quality control; Canadian Rockies; Waterton; Castle

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1. Summary

The Government of Alberta (GoA) introduced the "Water for Life" strategy [1], partly to ensure there will be sufficient provincial water resources available for ecosystem and anthropogenic needs. Mountain headwaters provide a high proportion of the available downstream runoff [2]; however, accurate measurement of mountain precipitation is a well-known challenge [3–6].

GoA Alberta Environment and Parks (AEP) and Agriculture and Forestry manage totalizing precipitation gauges throughout Alberta. On the eastern slopes of the Alberta Rocky Mountains, most gauges are sparsely located at valley and mid-mountain sites [7,8]. To further investigate mountain headwater precipitation regimes, the University of Lethbridge Artemis Lab (ULAL) installed three totalizing precipitation gauges at different elevations and in different landcover types, near to existing public gauges. One gauge was installed in an open alpine location, while the other two gauges were in valley sites, with one in a woodland clearing [9] and the other in a recently burnt area [10] of standing dead tree stems and sparce ground cover vegetation. It was noted in the WMO Fifth Session

Final Report, that the Solid Precipitation Intercomparison Experiment (SPICE) gauge management practices should follow the manufacturer's recommended installation and operational maintenance methodologies [11]. However, data obtained from research sites may not be reliable as a result of improper maintenance activities [12]. ULAL followed the manufacturer's recommended installation and maintenance routines for each totalizing precipitation gauge.

The data collected from the totalizing precipitation gauges are prone to noise and measurement errors [6,13,14], especially from the effects of wind-induced under-catch of snow entering the orifice [13,15]. Site characteristics such as the amount of natural canopy sheltering the gauge [12], as well as the installation of shielding to limit airflow around the gauge [16,17], decrease these errors. Other environmental and sensor configuration factors can result in evaporative losses, snow covering the orifice, or false measurements of precipitation when no event is in progress [11,16,18]. Observation quality control (QC) using data cleaning and filtering must be applied to time-series observations to remove noise and systematic measurement errors. Different techniques have been used to clean and smooth the precipitation datasets [12,14,19]. This paper explains the adjustments applied to the ULAL totalizing precipitation gauges for noise, as well as over- and under-catch, to show the relative proportions of error and potential range in accumulated precipitation in the data records. Two different procedures were used to perform QC adjustments to the precipitation observations collected in this region. The initial data filtering routine applied to the data was developed by the Alberta Climate and Information Service (ACIS) and used to ensure data consistency with publicly available precipitation datasets. Wind-induced bias corrections are not applied by ACIS; therefore, the rest of the QC routines used in this paper were developed by another research group [12]. Pan et al. [12] applied wind-induced bias adjustments to the precipitation data collected with the same sensor and shielding located in a similar Western Canadian region.

2. Data Description

The following three Geonor totalizing precipitation gauge sites were used: CMR (Castle Mountain Resort), WFS (Westcastle Field Station), and Cameron [20]. Datasets for each site containing variables required for the QC process (shown in Table 1) are available from the Federated Research Data Repository (FRDR) at https://doi.org/10.20383/102.0551 (accessed on 4 May 2022).

Table 1. Raw and processed data descriptions and units.

Variable	Value	Units	Description
Timestamp	recorded		Time measurement was recorded (yyyy–mm–dd hh:mm)
RH	recorded	%	Relative humidity
Wind	recorded	ms^{-1}	Wind speed
AirTemp	recorded	°C	Air temperature
In_SR	recorded	watt/m^2	Incoming solar radiation
Raw_Precip	recorded	mm	Raw precipitation record
ACIS_Precip	computed	mm	ACIS weighing gauge time-series data filtering
Noise_Precip	computed	mm	Noise removal of positive values during no precipitation
OC_Precip	computed	mm	Over-catch subtracted
UC_Precip	computed	mm	Under-catch added for snow and rain

The CMR Geonor was installed in September 2015; however, the record was not continuous until 2017. The WFS Geonor was installed in the summer of 2017, and both the WFS and CMR records used in this analysis were continuous for four hydrological years, starting from October 2017 through to September 2021. The Cameron Geonor dataset was continuous from the date of installation in October 2018 through to September 2021.

The CMR, WFS, and Cameron precipitation records were set to zero at the beginning of each hydrologic year (1 October) to match the publicly available historical meteorological data accessible from the Alberta Climate Information Service's (ACIS) [7] and Alberta Environment and Park's (AEP) "Alberta's River Forecast Centre: Awareness and Communication" system [21] datasets. The data collection interval for all three Geonor gauges was one measurement every 15 min. Fluid change jumps in the observed gauge level at biennial maintenance intervals were removed from each record.

3. Methods

3.1. Study Area

The study area was within the eastern slope headwaters of southwestern Alberta, Canada (Figure 1). ULAL installed three totalizing precipitation gauges—two in the West Castle Watershed (WCW) and one in the Waterton Lakes National Park (WLNP). The CMR gauge is located within the Castle Mountain Resort [22] along the Gravenstafel ridge on the western side of the WCW, at 2130 m above sea level (asl). The WFS gauge is situated at the University of Lethbridge Westcastle Field Station within the valley bottom of the WCW at 1400 m asl, 3 km northeast of CMR. The Cameron gauge is situated in the bottom of Cameron Valley at 1655 m asl, within Waterton Lakes National Park, 45 km southeast of WFS.

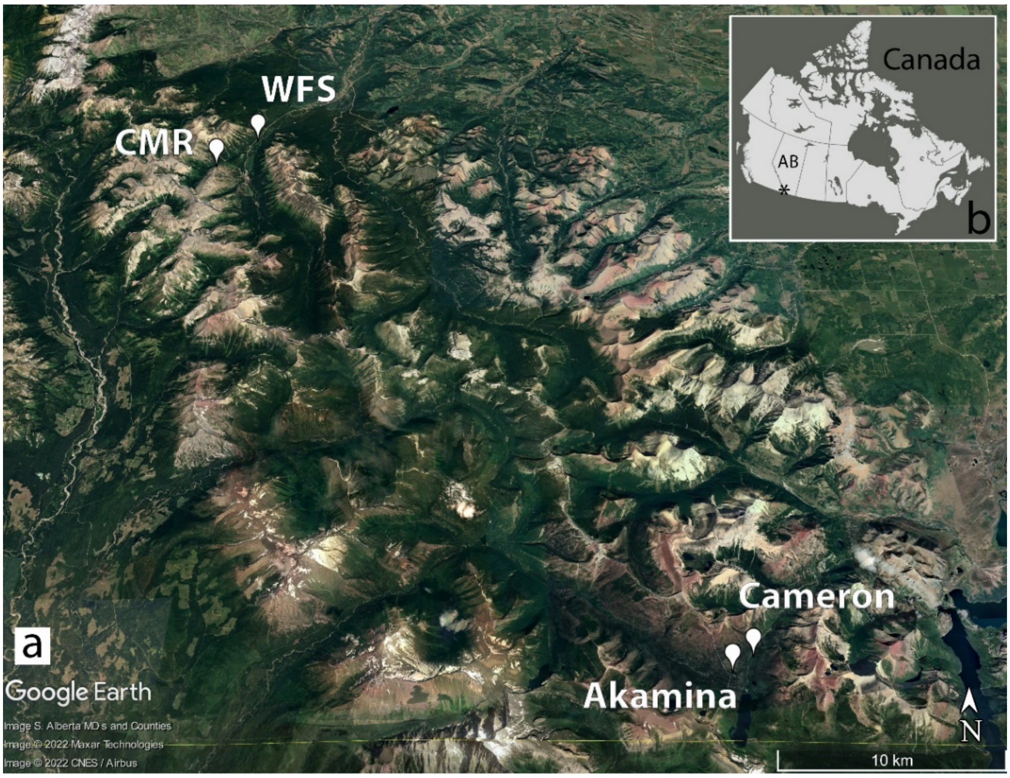
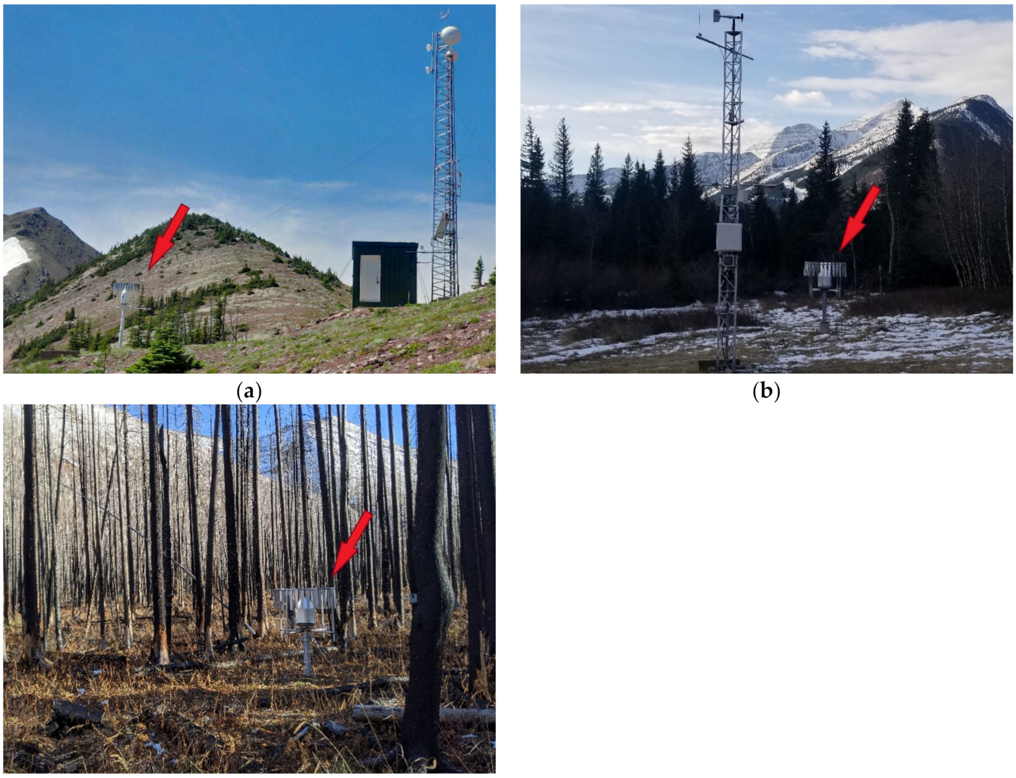


Figure 1. (**a**) Proximal locations of the CMR, WFS, and Cameron Geonor gauge sites. The AEP Akamina (mid-mountain site at an elevation of 1809 m asl) provides publicly available precipitation data. (**b**) Inset: study area in the Canadian Rockies of southwestern Alberta, Canada.

3.2. Sensor Specifications

Geonor T-200B [14,23] precipitation gauges with single alter wind screens and several weather sensors recording incoming shortwave radiation, air temperature, relative humidity, and wind speed were installed by the University of Lethbridge (Figure 2) at the CMR ridge (a), WFS valley (b), and Cameron valley (c) locations. Glycol (40%)/methanol (60%) antifreeze and a $\geq$ 500 mL mineral oil surface sealant were added to the Geonor gauges using standard Campbell Scientific (CS) specifications [24]. Standard and consistent CS CR1000 [25] datalogger programming was used at all three locations.



(**a**) (**b**) (**c**)

Figure 2. Site photographs showing the totalizing precipitation gauge terrain and vegetation conditions, and adjacent weather stations: (**a**) CMR, (**b**) WFS, and (**c**) Cameron (the weather station is behind the observer, so it is not shown).

The CMR precipitation gauge has the largest capacity 1500 mm Geonor bucket, with three vibrating wires to accommodate less frequent site visits and occasional turbulent wind conditions over the ridge. The site was selected for ease of access for maintenance activities, as well as to connect to the tele-communication and power infrastructure provided by the Castle Mountain Resort. The gauge is mounted on a tall pedestal to keep it above snow drifts and low-level blowing snow, but because it is at the upper limit of the tree line, there is minimal surrounding vegetation to shelter the gauge from strong turbulent winds. The CMR weather station is in the field of view (FOV) of a web camera located lower down the mountain side, and another web camera is located adjacent to the gauge site so that the Geonor gauge and sky conditions can be monitored.

The CMR windspeed sensor malfunctioned from 1 November 2018 to 14 February 2019, resulting in a data gap. The missing CMR windspeed data (15 min averages) were gap filled by regression to a nearby weather station on the resort ~200 m lower down the mountain side ($r^2 = 0.81$).

A smaller 600 mm capacity Geonor gauge was installed at the WFS weather station (Table 2) [9], as access is easy from a nearby highway, and site visits are frequent given this is a well-used university research station. This unit has a single vibrating wire, as it is located in a clearing surrounded by mixed deciduous and conifer trees, so wind conditions are more stable than the nearby CMR ridge. The gauge is in the FOV of a web camera located on the cabin of the field station. A 600 mm capacity single-wire Geonor gauge was installed at the Cameron valley research site (Table 2) within an area of mature pine forest that was killed and defoliated in the Kenow wildfire of September 2017 [10]. Publicly available precipitation data from the AEP Akamina site (Figure 1, located within 1.5 km of Cameron) were available for comparison.

Table 2. Geonor totalizing precipitation gauge and weather sensor specifications for the CMR, WFS, and Cameron sites.

Site	CMR	WFS	Cameron
Elevation	2130 m asl	1400 m asl	1655 m asl
Latitude	49°19′15.18″ N	49°20′55.17″ N	49°2′3.52″ N
Longitude	114°26′20.94″ W	114°24′39.01″ W	114°2′17.55″ W
Installation date	17 September 2015	7 September 2017	27 October 2018
Precipitation gauge	GEONOR T-200B-MD	GEONOR T-200B	GEONOR T-200B
Capacity	1500 mm	600 mm	600 mm
Precision vibrating wire	3	1	1
Incoming shortwave radiation	CS CMP3	CS CNR1	CS CNR4
Air temperature	CS T109	CS HC2S3	CS HMP45
Relative humidity	CS HMP45	CS HC2S3	CS HMP45
Wind speed	Met One 013A	RM Young 05103	RM Young 05103

3.3. Data Cleaning and Quality Control

Systematic measurement biases are common in totalizing precipitation gauges [6]. Figure 3 shows the processing workflow to clean the raw data and create each adjusted precipitation variable. Evaporative losses, sensor drift [14], and temperature- or wind-induced noise can lead to significant deviations in the data (Figure 4; raw measurements are displayed with a black line). Under-catch of snow [15,26] and rain [12] can occur as a result of wind across the gauge orifice. Over-catch of snow [6,16] can occur when there is no atmospheric precipitation and wind mobilizes the snow from the ground or surrounding canopy.

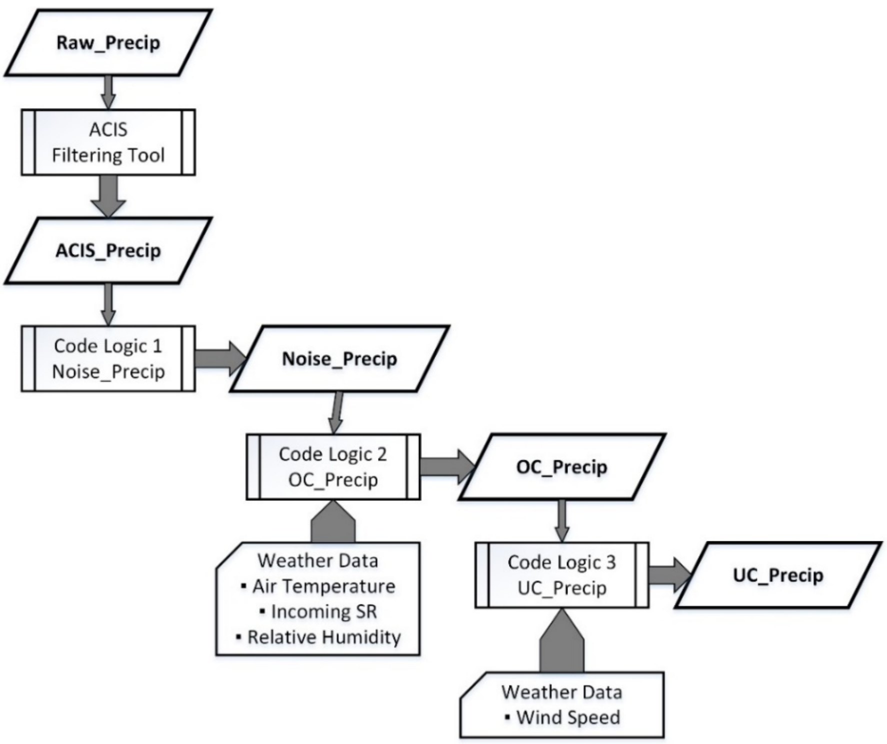


Figure 3. Quality control workflow diagram illustrating the sequence of steps to compute precipitation-adjusted variables, including the weather data used in each code logic block.

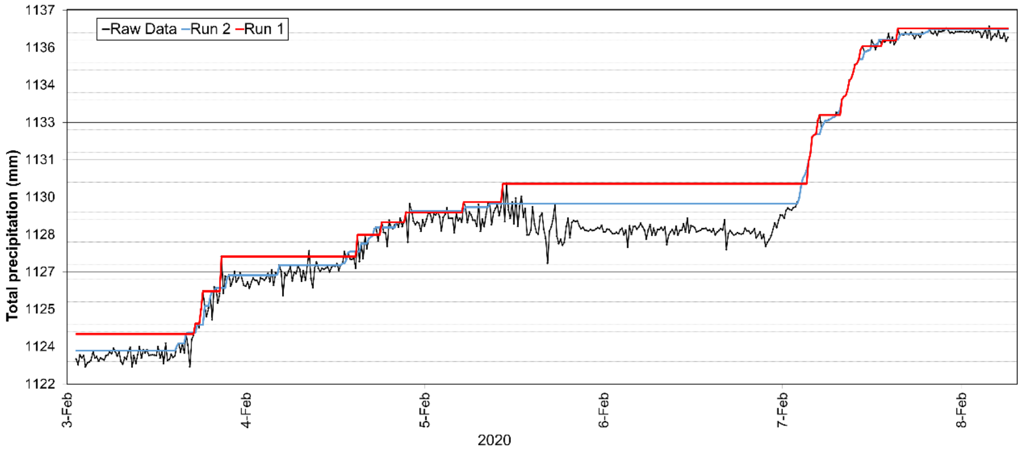


Figure 4. ACIS "weighing gauge time-series analysis and noise filtering tool" sample. Black line—raw data; red line—run #1; blue line—run #2.

An ACIS "weighing gauge time-series analysis and noise filtering tool" [27] was used to adjust the 15 min time-series observation values. This tool removes all negative accumulation, and the series is smoothed using a moving range window. The tool does not adjust for evaporative losses in the gauge. The ACIS filtering tool was run twice for all three Geonor time series (e.g., Figure 4). Once the tool completed its execution, a visual inspection was done to verify the filtered output. After several trial runs, the parameter settings listed in Table 3 were adopted for the ACIS_Precip variable. The second run (blue line) was used as the baseline for further adjustments.

Table 3. ACIS weighing gauge time-series analysis and noise filtering tool parameter settings per run.

Run #	Range	Change Factor	Raw Count	Comments
1 (red line)	24	0.2	3	
2 (blue line)	24	0.9	1	Baseline used for further adjustments

After the ACIS filtering tool execution was complete, further data cleaning was required to remove additional noise and adjust the time series for precipitation over- and under-catch [12,14]. Three additional cleaning routines were applied sequentially (as seen in Figure 3) to correct precipitation measurements. Two routines removed precipitation that did not belong in the time series, while the third added precipitation that was missed. Adjacent weather station sensor data (incoming shortwave radiation, air temperature, relative humidity, and wind speed) were used as inputs to the correction calculations. Table 4 lists the constants used in each code logic block (below) to compute data values for the removal of noise (Noise_Precip), over-catch (OC_Precip) from blowing snow, and under-catch (UC_Precip) of precipitation. The code logic blocks are executed sequentially for each 15 min observation (i), starting with the first observation in the data file and continuing to the end of the data file.

The noise (Noise_precip) that the ACIS tool did not filter out was subtracted from the record. This noise was defined as precipitation less than the $\text{Noise}_{\text{Threshold}}$, with no recorded measurements either before or after the observation (see Code Logic 1). The CMR noise threshold value was set to 0.11 mm, as in [12]. As a result of a single vibrating wire with no averaging [14], the WFS and Cameron gauges were more susceptible to noise than the CMR Geonor gauge, which had three vibrating wires that were averaged to a single measurement for each data record. The initial threshold setting was the same as CMR; however, it was adjusted using trial and error, until the noise signal was mitigated. The WFS and Cameron thresholds were set to 0.05 mm, which reduced the amount subtracted from the records.

Table 4. Data cleaning threshold parameter values used for each gauge site.

Threshold Values	CMR	WFS	Cameron	Comment
$Noise_{Threshold}$	0.11	0.05	0.05	Threshold for small positive precipitation changes
$In\_SR_{Threshold}$	300	300	300	Incoming SR threshold (daylight hours only)
$RH_{Threshold}$	75	65	65	RH threshold when SR is greater than $In\_SR_{Threshold}$
$AirTemp_{Threshold}$	0.0	0.0	0.0	Temperature threshold to separate snow/rain
WS_{Lower}	1.2	1.2	1.2	Lower wind speed bounds for under-catch
WS_{Upper}	6.5	6.5	6.5	Upper wind speed bounds for under-catch
$H_{anemometer}$	14.0	6.5	3.0	Height of anemometer (m)
H_{gauge}	3.0	2.0	1.75	Height of Geonor orifice (m)
Roughness	0.05	0.05	0.05	Roughness length (m)
CE_{Rain}	1.05	1.05	1.05	Catch efficiency multiplier for rain
WS_{gauge}		computed		Wind speed above the Geonor orifice
CE_{Snow}		computed		Catch efficiency for snow

Code Logic 1. *Noise_Precip (small positive observations when no apparent precipitation event occurs)*

For each observation i starting with the first observation to the end of the file:
  IF ACIS_Precip $_i$ < $Noise_{Threshold}$
  Then IF ACIS_Precip $_{i-1}$ > 0 or ACIS_Precip $_{i+1}$ > 0
    Then Noise_Precip $_i$ = ACIS_Precip $_i$
    Else Noise_Precip $_i$ = 0
  Else Noise_Precip $_i$ = ACIS_Precip $_i$
End.
□

The next step was to subtract the over-catch (OC_Precip) due to blowing snow that was unlikely to result from atmospheric precipitation (see Code Logic 2). For CMR and WFS, the presence of over-catch during non-precipitation blowing snow conditions could be manually checked by reviewing the coincident camera imagery. While wind data have potential as a proxy for blowing snow [12] inputs, they were found to be unreliable as an automated data filtering variable because of occasional anemometer riming [16] at temperatures near to 0 °C, and because of the high frequency of winter blizzards where both wind and precipitation display high but uncorrelated values. Therefore, over-catch corrections were limited to precipitation recorded at temperatures below the rain/snow threshold ($AirTemp_{Threshold}$). As snow pellets can be present in the rain and snow, the $AirTemp_{Threshold}$ was set to 0 °C [28]. A relative humidity threshold ($RH_{Threshold}$) was used to further selectively subtract the recorded precipitation. An incoming solar radiation threshold ($In\_SR_{Threshold}$) was used to remove the daytime blowing snow. To calibrate the $In\_SR_{Threshold}$, camera imagery was used to manually verify whether or not blowing snow occurred above or below a certain value. Threshold values for CMR were set to $In\_SR_{Threshold}$ (300 watt/m^2) and $RH_{Threshold}$ (75%) based on expert judgment, combined with blowing snow observations in web cam imagery. The $RH_{Threshold}$ was set to 65% for WFS to prevent precipitation events from being removed from the data record when there was low incoming solar radiation ($In\_SR_{Threshold}$, 300 watt/m^2) using camera imagery. As the Cameron site does not have a camera, the same $In\_SR_{Threshold}$ (300 watt/m^2) and $RH_{Threshold}$ (65%) threshold values were adopted as WFS owing to the similar gauge height and environmental characteristics.

Code Logic 2. *OC_Precip (remove over-catch from blowing snow using air temperature, In_SR, and RH thresholds)*

For each observation i:
IF Noise_Precip $_i$ > 0
Then IF AirTemp $_i$ > $\text{AirTemp}_{\text{Threshold}}$
Then OC_Precip $_i$ = Noise_Precip $_i$
Else IF RH $_i$ < $\text{RH}_{\text{Threshold}}$
Then OC_Precip $_i$ = 0
Else IF In_SR $_i$ > $\text{In\_SR}_{\text{Threshold}}$
Then OC_Precip $_i$ = 0
Else OC_Precip $_i$ = Noise_Precip $_i$
Else OC_Precip $_i$ = 0
End.
□

The last QC step was an under-catch (UC_Precip) correction for snow and rain (see Code Logic 3) using the formula and thresholds developed for a similar Rocky Mountain site in Western Canada [12]. A lower (WS_{Lower}) and upper (WS_{Upper}) bound was used to limit the range for wind speed correction. Wind speed above the Geonor (WS_{gauge}) was calculated using the height of the wind speed sensor ($\text{H}_{\text{anemometer}}$), the height of the gauge orifice (h_{gauge}), and a roughness length parameter. The roughness length for all of the sites was set to 0.05, as each location has low-level vegetation. No further precipitation adjustment was applied for wind speeds below the lower threshold. Wind speeds above the upper threshold were set to the upper wind speed threshold value [12,16]. The catch efficiency for snow (CE_{Snow}) was calculated using the wind speed above the gauge orifice. The catch efficiency for rain (CE_{Rain}) was set to a constant value. Setting the CMR gauge upper wind speed threshold to 9 ms^{-1}, as in [12], caused the under-catch to be amplified by an unreasonable amount during the snow season, so an upper limit of 6.5 ms^{-1} was used, as this is typical for Arctic and northern regions [12].

Code Logic 3. *UC_Precip (under-catch correction for snow and rain using wind speed at the top of the gauge)*

For each observation i:
$\text{WS}_{\text{gauge }i} = \text{Wind}_i \times (ln(\text{h}_{\text{gauge}}/\text{Roughness})/ln(\text{H}_{\text{anemometer}}/\text{Roughness}))$

IF $\text{WS}_{\text{gauge }i}$ > WS_{Upper}
Then $\text{WS}_{\text{gauge }i}$ = WS_{Upper}

IF OC_Precip $_i$ > 0
Then IF $\text{WS}_{\text{gauge }i}$ > WS_{Lower}
Then IF AirTemp $_i$ < $\text{AirTemp}_{\text{Threshold}}$
Then
$\text{CE}_{\text{Snow}} = 1.18\ \text{e}^{-0.18 \times \text{WSgauge}}$
UC_Precip $_i$ = OC_Precip $_i$/CE_{Snow}
Else UC_Precip $_i$ = OC_Precip $_i$ × CE_{Rain}
Else UC_Precip $_i$ = OC_Precip $_i$
Else UC_Precip $_i$ = OC_Precip $_i$
End.
□

The CMR, WFS, and Cameron Raw_Precip, ACIS_Precip, Noise_Precip, OC_Precip, and UC_Precip data were aggregated to daily, monthly, and annual totals. For each year in the CMR, WFS, and Cameron annual datasets, Code Logic 4 was used to calculate the amount of precipitation adjustment for each variable in the cleaning workflow.

Code Logic 4. *Amount of precipitation adjustment for each variable in the cleaning workflow*

For each year in the dataset:
  ACIS-filter = ACIS_Precip − Raw_Precip
  Noise-reduction = Noise_Precip − ACIS_Precip
  Over-catch = OC_Precip − Noise_Precip
  Under-catch = UC_Precip − OC_Precip
  Total Correction = UC_Precip − Raw_Precip
End.
□

4. Aggregated Precipitation Output Results and Discussion

For comparison purposes, Figure 5 shows the cumulative ACIS_precip time series for CMR, WFS, and Cameron. It also includes the public AEP Akamina Pluvio totalizing precipitation gauge record, which is 1.5 km away and 154 m higher in elevation than the Cameron gauge. Although the data were collected from two different gauge types, studies have shown Geonor and Pluvio measurements are comparable [16]. The AEP public records do not have the noise reduction or the under- or over-catch corrections applied [29], so the Akamina record is most comparable to "ACIS_Precip". The Akamina record tends to show a >10% increase over Cameron because of its higher elevation and rain shadow effect on the lee side of the mountain slope [30], but the timing and magnitude of precipitation events are visibly synchronous.

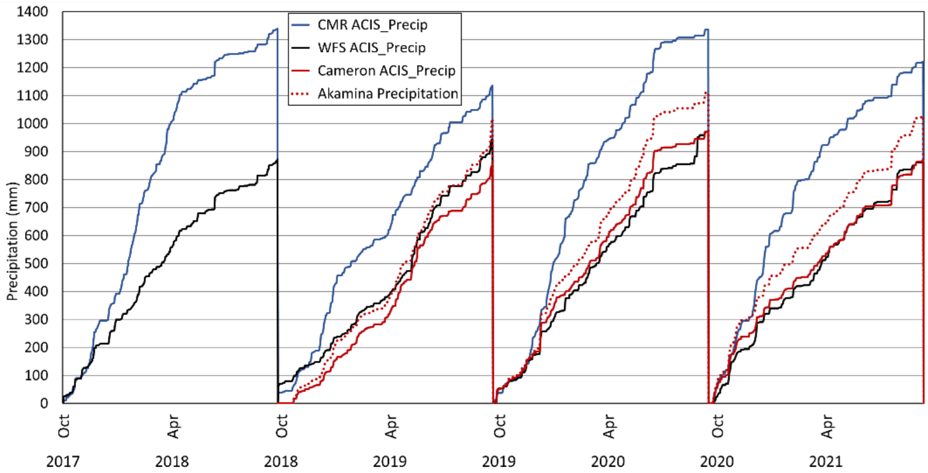


Figure 5. Cumulative precipitation of ACIS_Precip for CMR, WFS, and Cameron. The Akamina (dotted line) site is in close proximity to Cameron and illustrates a publicly available precipitation dataset that is comparable to ACIS_Precip.

For each site, Figure 6 presents the magnitude of each cumulative precipitation correction (ACIS_Precip, Noise_Precip, OC_Precip, and UC_Precip) relative to the Raw_Precip baseline through time. The adjustments for CMR (Figure 6a), WFS (Figure 6b), and Cameron (Figure 6c) are plotted for each hydrologic year.

The Raw_precip and ACIS_precip daily total precipitation values did not deviate significantly. The WFS and Cameron valley-level gauges measured similar depths of precipitation for the years of comparable data. Similar to CMR, both gauges demonstrated minimal difference between the Raw_Precip measurements and ACIS_Precip filtered data.

There was a small amount of noise (Noise_Precip) in the CMR gauge that contributed approximately 1 to 2 mm per month. WFS and Cameron were more susceptible to noise during the colder winter months when most of the annual Noise_Precip adjustment occurred. Cameron had a higher amount of noise compared with WFS, which was possibly a function of the different canopy cover or wind turbulence surrounding the gauge sites.

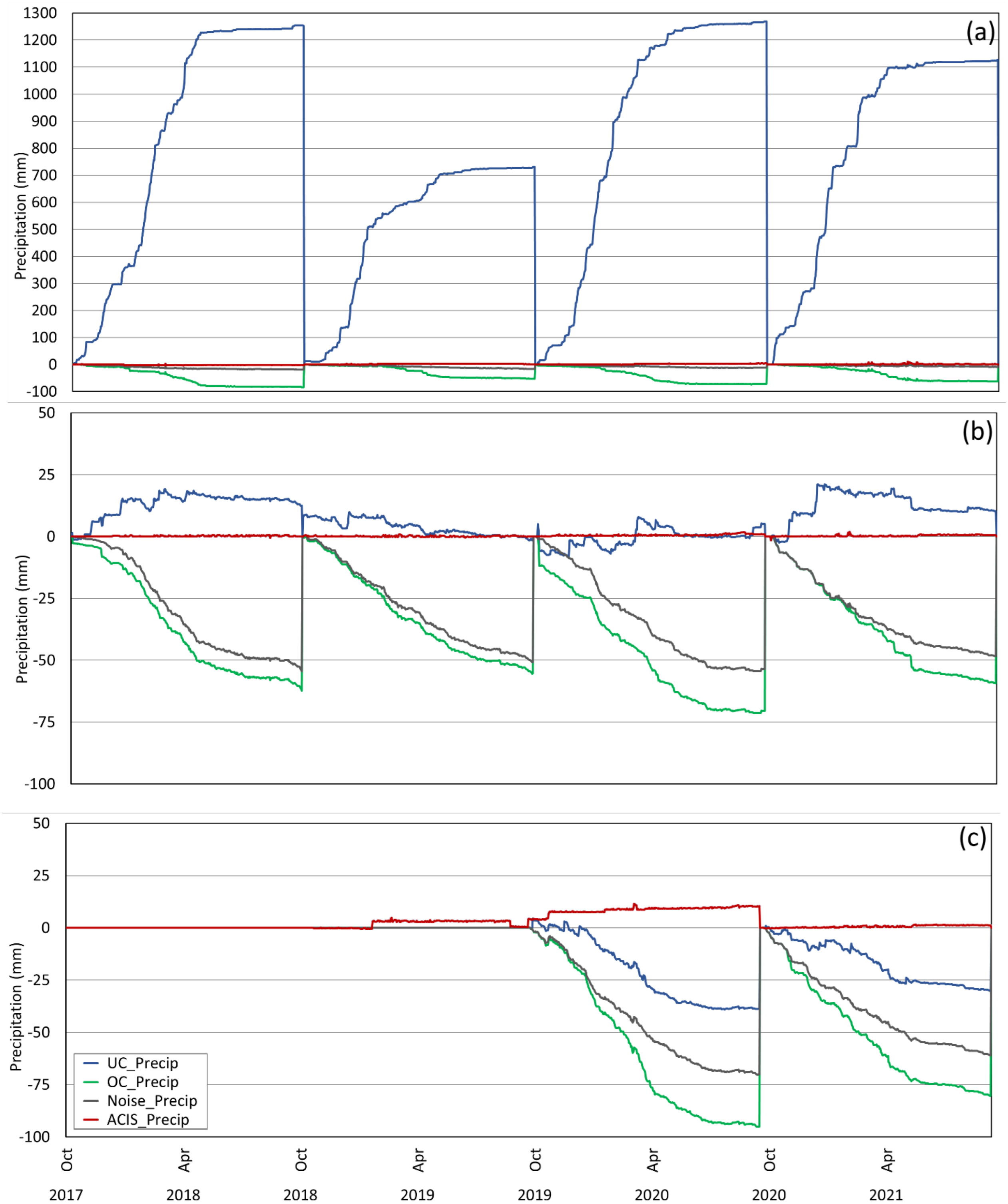


Figure 6. The relative ACIS_Precip, Noise_Precip, OC_Precip, and UC_Precip deviations from the Raw_Precip baseline for (**a**) CMR, (**b**) WFS, and (**c**) Cameron.

Over-catch (OC_Precip) corrections on the CMR ridge were prevalent in the late winter and spring months, accounting for an additional 36 mm to 65 mm per year. The WFS and Cameron valley sites demonstrated a blowing snow over-catch correction, ranging from 5 mm to 76 mm, occurring either in October or the spring time frame, presumably due to warmer temperatures and less mobile snow.

Under-catch (UC_Precip) corrections at all sites were the greatest during snow cover months from September through to late spring. WFS under-catch corrections were frequent between October to April, while for Cameron, they occurred primarily from October to February and, to a lesser degree, during March to May. The under-catch code logic was sensitive to high wind speeds, especially during snowfall events.

The high-elevation CMR ridge gauge recorded the highest annual precipitation of all of the gauges (see Figure 5). The annual CMR ACIS-filtered record (Table 5) was within a few millimeters of the raw precipitation measurements. Of the three sites, CMR displayed the largest annual total correction, ranging between 39.2% to 48.8%, with under-catch representing the largest correction factor at up to 51.5% of the annual total for 2017–2018 and 2019–2020. This represents an approximate doubling of the raw precipitation observations for the alpine ridge location, although this is a plausible amplification of the annual precipitation, given it is known that the mean winter snow accumulations at these alpine elevations can exceed valley depths by a factor of four [31]. WFS displayed between −0.1% to 1.4% precipitation correction, with Cameron showing a −4.2% to −3.6% annual decrease. The removal of noise and adding an under-catch correction were the most impactful adjustments for the valley gauges, resulting in an almost net zero annual change in precipitation measurement.

Table 5. Annual amount of precipitation adjustment for each variable in the cleaning workflow in millimeters (amount of adjustment as a percentage is listed in the brackets) computed using Code Logic 4. Weather station data were not complete for Cameron during its first year of operation, so the complete QC process was only applied to the last two hydrologic years (2019–2021).

Correction	2017–2018 mm (%)	2018–2019 mm (%)	2019–2020 mm (%)	2020–2021 mm (%)
CMR				
ACIS filter	−2.1 (−0.2%)	1.6 (0.1%)	4.7 (0.4%)	1.4 (0.1%)
Noise reduction	−17.5 (−1.3%)	−18.6 (−1.6%)	−15.9 (−1.2%)	−10.2 (−0.8%)
Over-catch	−64.6(−5.1%)	−36.0 (−3.3%)	−60.0 (−4.8%)	−54.1 (−4.7%)
Under-catch	1342.0 (51.5%)	783.7 (42.0%)	1340.3 (51.5%)	1189.7 (50.7%)
Total correction	1258.1 (48.3%)	730.7 (39.2%)	1269.1 (48.8%)	1126.9 (48.0%)
WFS				
ACIS filter	0.2 (0.0%)	0.1 (0.0%)	0.9 (0.1%)	0.5 (0.1%)
Noise reduction	−54.7 (−6.2%)	−50.8 (−5.4%)	−54.5 (−5.6%)	−48.9 (−5.7%)
Over-catch	−7.8 (−1.0%)	−4.6 (−0.5%)	−16.9 (−1.9%)	−10.9 (−1.4%)
Under-catch	74.9 (8.4%)	53.9 (5.7%)	75.6 (7.7%)	69.5 (8.0%)
Total correction	12.6 (1.4%)	−1.4 (−0.1%)	5.1 (0.5%)	10.2 (1.2%)
Cameron				
ACIS filter			6.4 (0.7%)	1.2 (0.1%)
Noise reduction			−76.4 (−7.9%)	−62.1 (−7.2%)
Over-catch			−24.9 (−2.9%)	−19.4 (−2.5%)
Under-catch			56.5 (6.1%)	50.2 (6.0%)
Total correction			−38.5 (−4.2%)	−30.1 (−3.6%)

5. Conclusions

This study applied data cleaning and QC to raw Geonor totalizing precipitation gauge records for three sites in the Canadian Rockies. The filtered ACIS_Precip and Raw_Precip data series were tracked closely together for all three gauges at daily and longer time increments. Despite being in a more severe wind environment, the annual noise in the CMR ridge record was small (10 mm to 20 mm) compared with the WFS (49 mm to 55 mm) and Cameron (62 mm to 76 mm) valley gauges as a result of the real-time averaging of the three vibrating wires relative to the single vibrating wire of the valley sites. The annual amount of CMR blowing snow over-catch correction was 36 mm to 65 mm; for WFS, it was 5 mm to 17 mm; and for Cameron, it was 19 mm to 25 mm. This correction was applied for measurements occurring throughout the day. However, using incoming solar radiation, additional corrections were possible during daylight hours. During non-daylight hours, it was not possible to reliably separate blowing snow from blizzard conditions, which suggests the total over-catch in the records may be slightly higher than what was estimated. The CMR record was most sensitive to under-catch corrections (731 mm to 1342 mm) as a result of high wind speeds in the turbulent ridge environment. This was mostly associated with the WS_{Upper} threshold value and is therefore sensitive to changes in this parameter value. The under-catch for WFS and Cameron was significantly less than that of CMR, ranging from 50 to 76 mm. This study illustrates that, with all QC adjustments applied, total precipitation records ranged between small corrections of ~−4% to 1% for valley locations up to ~49% for alpine ridge locations. Therefore, without applying such data cleaning and QC procedures, significant errors would be propagated into headwater water balance or precipitation orographic enhancement estimates derived from such records.

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Data Availability Statement: The raw and processed precipitation and supplemental meteorological datasets are available for download from the Federated Research Data Repository: https://doi.org/10.20383/102.0551 (accessed on 4 May 2022) under Creative Commons Attribution 4.0 International (CC BY 4.0) license.

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