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Water Resources Research

RESEARCH ARTICLE

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Key Points:

- Rainfall in windy upland areas can be greatly underestimated due to wind-induced undercatch
- The mounting height and shape of a rain gauge is more important for accurate rainfall measurement than is widely appreciated
- An improved-aerodynamic rain gauge shape is the simplest and cheapest method of enhancing rainfall catch

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Quantifying and Mitigating Wind-Induced Undercatch in Rainfall Measurements

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Abstract Despite the apparent simplicity, it is notoriously difficult to measure rainfall accurately because of the challenging environment within which it is measured. Systematic bias caused by wind is inherent in rainfall measurement and introduces an inconvenient unknown into hydrological science that is generally ignored. This paper examines the role of rain gauge shape and mounting height on catch efficiency (CE), where CE is defined as the ratio between nonreference and reference rainfall measurements. Using a pit gauge as a reference, we have demonstrated that rainfall measurements from an exposed upland site, recorded by an adjacent conventional cylinder rain gauge mounted at 0.5 m, were underestimated by more than 23% on average. At an exposed lowland site, with lower wind speeds on average, the equivalent mean undercatch was 9.4% for an equivalent gauge pairing. An improved-aerodynamic gauge shape enhanced CE when compared to a conventional cylinder gauge shape. For an improved-aerodynamic gauge mounted at 0.5 m above the ground, the mean undercatch was 11.2% at the upland site and 3.4% at the lowland site. The mounting height of a rain gauge above the ground also affected CE due to the vertical wind gradient near to the ground. Identical rain gauges mounted at 0.5 and 1.5 m were compared at an upland site, resulting in a mean undercatch of 11.2% and 17.5%, respectively. By selecting three large rainfall events and splitting them into shorter-duration intervals, a relationship explaining 81% of the variance was established between CE and wind speed.

Plain Language Summary This study was motivated by how challenging it is to measure rainfall accurately, despite it appearing to be very simple. Rainfall measurement is important to society because it has so many everyday uses, such as food production and weather forecasting, and applications that are critical to life, such as flood warning and effective management of water resources. Rainfall is difficult to measure because it varies so much in time and space, and the measurement of rain is highly affected by how windy it is, which also varies in time and space. Therefore, when it rains at the same time as being very windy, which is common during many storms, rainfall measurements are greatly underestimated. The uplands generally receive more rainfall and higher wind speeds than the lowlands, therefore it follows that we underestimate rainfall by more in the uplands. This is important because rainfall measurements in the uplands are sparse, yet it is in such areas where many floods originate. This study shows that the underestimation of rainfall at a site in the windy Scottish uplands was more than 23% on average. It then suggests some techniques that can be implemented to improve the measurement of rainfall.

1. Introduction

Despite the apparent simplicity, it has proven notoriously difficult to measure rainfall accurately because of the challenging environment within which it is measured, and in particular because of wind. Long-term reference rainfall measurements that reflect best practice are of critical importance. Applications ranging from flood risk management and water resources planning to numerical weather prediction and urban sewer design rely heavily on accurate rainfall measurements. However, systematic bias caused by wind is inherent in rainfall measurement and introduces an unquantified error into hydrological science that is generally ignored.

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Despite technological developments over the past 50 years, Tipping Bucket Rain Gauges (TBRs) remain the most widely used and trusted providers of rainfall data. Their specific shortcomings are well documented (Habib et al., 2001, 2008; La Barbera et al., 2002; Molini et al., 2005), yet there is little choice but to retain them. They provide useful information and are cost effective. However, TBRs could be utilized more effectively with the international adoption of standardization procedures by rain gauge manufacturers and data practitioners, a process initiated by BSI (2012) and CEN (2012).

Rain gauge errors may be categorized broadly as instrumental or environmental. The former relate to the ability of an instrument to report correctly the rainfall and are resolved by appropriate laboratory calibration. Their nature and extent depends upon the measuring principle. For TBRs, instrumental errors are addressed comprehensively by Lanza and Stagi (2009). Environmental errors occur when rain collected by an exposed gauge is less than that which would have fallen on the ground if the gauge was not there. These type of errors are generic to all catching-type rain gauges mounted above the ground regardless of measuring principle and are often more challenging to resolve. Splash in/out and evaporation are examples of environmental error but the most significant is caused by wind (Rodda & Dixon, 2012).

Wind-induced undercatch is a well-known but poorly quantified phenomenon. The term is commonly used to explain why a rain gauge mounted with the orifice at ground level collects more rainfall than an adjacent gauge mounted above the ground. This observation is documented extensively in the literature (Alter, 1937; Goodison et al., 1998; Jevons, 1861; Kurtyka, 1953; Pollock et al., 2014; Rodda, 1968; Sevruk & Hamon, 1984). A generally accepted theory is that it is due to a combination of accelerated wind and increased turbulence above the gauge orifice, causing rain to be deflected away from an exposed rain gauge, with site-specific turbulence complicating the relationship (Larson & Peck, 1974). The shape of the exposed gauge is reported to have a significant impact on the airflow above the gauge orifice (Folland, 1988). Computational Fluid Dynamics (CFD) simulations are consistent with this finding, showing also that improved-aerodynamic gauges reduce turbulence and produce recirculating airflow structures above the orifice, which is thought to improve Catch Efficiency (CE) (Colli et al., 2017). CE is defined as the ratio of a nonreference measurement to a reference measurement. However, evidence based on field observations quantifying the effect of gauge shape on CE is lacking. Sieck et al. (2007) reported that simple preventative measures using innovative gauge designs that are aerodynamically less intrusive result in improved data quality. Despite this, international uptake of designs such as by Folland (1988), Chang and Flannery (2001), and Strangeways (2004) has been limited.

The validity and intercomparability of rainfall studies relies heavily upon the derivation of the reference rainfall measurement. A broad range of shielding configurations are used to shelter rain gauges from wind (Yang et al., 1999). However, rain gauge windshields can be cumbersome and expensive. The most widely accepted method of minimizing the wind effect on rainfall measurements is to adopt the use of a pit rain gauge (CEN, 2010). The most recent international field intercomparison on rainfall intensity used this standard to develop a field reference measurement (Lanza & Stagi, 2009). However, it is rarely practicable to install a pit gauge and uptake has been limited.

Using a pit gauge as a reference, efforts have been made to correct for wind-induced undercatch. Duchon and Essenberg (2001) report 4% undercatch between pit and above-ground gauges during typical rainfall events but were unable to develop a relationship with wind speed. Sieck et al. (2007) observed differences in catch between reference and nonreference measurements typically of the order of 2–10%, but found that Nešpor and Sevruk's (1999) numerical-simulation derived correction technique using drop-size distribution to be less effective than a correction based on wind and rainfall rate only. Note that corrections have been developed for snow (Kochendorfer et al., 2017; Wolff et al., 2015; Yang, 2014). However, snow measurements are outside the scope of this study.

Hydrological modeling applications often assume rain gauge data are reference measurements, without understanding limitations, applying a suitable correction, or accounting for input-data uncertainty. The implications of a large unreported undercatch on applications such as real-time flood forecasting may be significant. In the UK and elsewhere, the windiest conditions often occur concurrently with large frontal rainfall events, such as those that caused devastation in the UK during the winter of 2015/2016, which are reported in this study. Archer et al. (2007) reported that during a large frontal event, the catchment water balance showed that the rainfall measured was less than the runoff generated. Globally, many floods

originate in upland areas where rainfall measurements are sparse and subject to wind-induced undercatch. Understanding rainfall processes better in the uplands is critical to reducing flood risk.

This study's aim is to quantify the typical error in rainfall measured by TBRs in windy conditions, focusing on developing understanding of the wind-induced undercatch and identifying what practical measures can be taken to improve rainfall measurement accuracy. A data-recording scheme for TBR data along with datalogging equipment commonly used by National Meteorological and Hydrological Services (NMHSs) is adopted to help understand the extent and implications of wind-induced undercatch within their rain gauge networks. The impact of an improved-aerodynamic shape on rainfall CE is quantified by field observations using a pit gauge as a reference and a conventional cylinder shape gauge, used internationally, as a comparison. The impact of gauge mounting height above the ground surface is also considered, relevant due to the different mounting conventions used globally by NMHSs. This study will also attempt to develop a relationship between CE and wind speed at different time aggregations, presenting an estimate of the typical undercatch in rainfall measurements at different wind speeds, and a correction relationship.

2. Methods

2.1. Site Descriptions

The UK experiences frequent concurrent high wind and rain events enabling investigation of wind-induced undercatch. The climatology of the UK is such that prevailing winds from the west or southwest deliver more rainfall to the west, where it is orographically enhanced by mountainous terrain (Fairman et al., 2015).

Two sites, one in the lowlands and one in the uplands, were instrumented to investigate and quantify the wind effect on rainfall measurements. The lowland site is located at Nafferton Farm in the north-east of England, 20 km west of Newcastle upon Tyne (Figure 1, left plot). Its elevation is 110 m and it is categorized as a lowland site. The upland site is located at Talla Water in south-west Scotland (Figure 1, right plot); it is categorized as an upland site with an elevation of 440 m. These sites are henceforth referred to as lowland and upland, respectively. The annual number of rain-days greater than 10 mm is on average 20–25 at the lowland site, and more than 60 at the upland site. Long-term average annual rainfall is 700–1,000 mm at the lowland site, compared to 2,000–3,000 mm at the upland site. The two sites are only 110 km apart, but the large difference in heavy-rain-days is largely due to orographic enhancement of frontal rainfall in the west, and a rain shadow effect in the east. The average annual 2 m wind speed at the lowland site is estimated as 4–5 m/s, whereas at the upland site this figure is around 10 m/s (UK Met Office, 2017).

Near the center of the foreground in both plots in Figure 1 is a metal antispash grid structure located at ground level. This is the reference pit containing rain gauges. The pit at the lowland site is large and contains two TBRs. The pit at the upland site is smaller and contains one TBR.




2.2. Rain Gauge Selection and Siting

Three types of TBR were used; they are included in Table 1 with the rationale for their selection. All three TBRs have a nominal bucket tip resolution of 0.2 mm. The ARG100 and the SBS500 have improved-



Figure 1. (left) Nafferton Farm lowland-east research site and (right) Talla Water upland-west research site.

Table 1
Displaying Gauge Models, Description, Rationale for Selection and Estimated Number Operational for Three TBRs Used in This Study

Gauge model details:				
1. Name				
2. Profile shape				
3. Acronym	Gauge image	Description	Selection rationale	Estimated number operational
ARG100 Improved-aerodynamic ARG		Plastic improved-aerodynamic gauge developed in the UK by Institute of Hydrology (IoH) in 1980s (Folland, 1988)	Improved aerodynamic properties to reduce extent of wind-induced undercatch	UK: 400 Global: 6000
SBS500 Improved-aerodynamic SBS		Aluminum improved-aerodynamic gauge using Folland (1988) and improved by Strangeways (2004)	Further improved aerodynamic properties to reduce extent of wind-induced undercatch	UK: 400 Global: 1000
Casella Conventional cylinder CAS		Conventional cylinder or 'straight-sided' rain gauge	Most global TBR monitoring networks use gauges of this shape	UK: >1000 Global: Tens of thousands

aerodynamic profiles. The Casella has a conventional cylinder profile which is the most commonly used TBR gauge shape used globally. At the lowland site, two SBS500 rain gauges were mounted in the pit with gauge orifice height at 0.0 m, and one adjacent to the pit, several meters away, on the ground, with its rim at 0.5 m. The Casella rain gauge was also mounted at 0.5 m several meters from the pit. At the upland site, three ARG100 rain gauges were mounted; in the pit at 0.0 m, at 0.5 m and at 1.5 m. The Casella rain gauge was mounted at 0.5 m, also adjacent to the pit. At both lowland and upland sites the gauges mounted above the ground adjacent to the pit were located perpendicular to or downwind of the prevailing wind, to reduce their interference with the pit. Henceforth, the ARG100 is referred to as the "ARG," the SBS500 as the "SBS" and the Casella as the "CAS." The two pit gauges at the lowland site are referred to as "Pit SBS 1" and "Pit SBS 2." While the ARG and the SBS are both treated as improved aerodynamic gauges, there are some differences in their respective characteristics, with the former being more prone to outsplash during higher intensity rainfall events (Strangeways, 2004). It was not possible to compare the ARG and SBS directly due to the different gauge type at each site.

Rain gauges mounted with the rim at 0.5 and 1.5 m are standard practice for many NMHSs, for example, the UK Met Office (UKMO) and KNMI in the Netherlands (both approximately 0.5 m). By using adjacent rain gauges of the same model with the same performance characteristics, calibrated in the same way, any differences above a residual instrumental error between the measurements captured above ground and those in the pit are primarily attributable to the wind effect. This is an assumption also used by Sieck et al. (2007).

2.3. Laboratory Calibration

All TBRs included in the experiment were calibrated individually by volumetric calibration. This process involved carefully balancing the bucket mechanism, passing 1 L of water through each gauge, counting the number of tips and calculating the exact resolution of the tipping bucket. The calibration intensity selected was 16 mm/h, considered a representative intensity for UK rainfall. Industry standard practice is not to use the specific calibration factor, instead using the nominal value of the tipping bucket, in this case 0.2 mm. However, to reduce the instrumental error, each gauge-specific calibration factor was applied in this study.

2.4. Data Collection

At both sites, the number of tips occurring in each minute was recorded using the Campbell Scientific CR1000 datalogger. These are, respectively, the TBR data-recording scheme and the datalogger used by the UKMO. Maximum and average measurements of wind at 0.5 and 2 m were available at 1 min resolution. The devices used were the Vaisala WXT520 and the Gill Instruments WindSonic[®], which both use ultrasonic technology to measure wind speed and direction. Ancillary meteorological measurements were also available; temperature was used in this study to determine whether a rainfall event could contain solid or mixed precipitation. At the lowland site, data were available between October 2014 and June 2016, spanning approximately 20 months. At the upland site, 14 months of data were available, from May 2015 to July 2016.

2.5. Rain Gauge Errors

As already discussed, types of error can be categorized into two groups, but errors specifically related to TBRs are outlined as follows. Instrumental errors include; mechanical error at different intensities, repeatability of the tipping bucket mechanism, gauge blockage, electronic and data logging errors. The instrumental errors were reduced in the laboratory by appropriate calibration and in the field by the use of quality equipment, maintained regularly. Moreover, the discrete sampling mechanism of the TBR results in local random quantization errors which are significant during light rainfall (Habib et al., 2013).

The TBR data collection strategy adopted in this study counted the number of tips that occurred within each minute. Local random errors are exacerbated by a discrete TBR data collection strategy which limits analysis of low intensity rainfall at short time scales (Ciach, 2003; Habib et al., 1999, 2001). However, it was adopted because it is commonly used in operational practice by NMHSs, therefore the analysis following also presents an appraisal of using this TBR data collection strategy.

Environmental errors may include; evaporation of rainfall not yet accounted for (in the funnel or on the tipping bucket mechanism), splash in/out of rain drops, adhesion/wetting and the wind-induced error which is exacerbated by gauge shape and mounting height. For two adjacent gauges of the same model and mounting height, the environmental errors should be comparable in magnitude.

2.6. Rainfall Events Selection

Processing was carried out to retrieve rainfall events and remove periods of no rain. Rainfall events can be defined in many ways depending upon the purpose of a chosen application (Dunkerley, 2008a), but are defined in this study as periods of rainfall, detected by the pit gauge, prior to and after which there has been no rain for a specified period of time. This duration is known as the "minimum inter-event time," MIT, and is usually between 0.25 and 24 h in most hydrological studies (Dunkerley, 2008b). An MIT of 4 h was selected as a compromise between too many events of inadequate size and too few events for meaningful statistics to be developed. A base data set was created for the lowland and upland sites comprising 52 and 83 events, respectively, with a minimum event threshold of 5 mm. Subsequent analyses splits these events into shorter-duration intervals so that the averaged wind speeds within each interval are more representative than the event-scale averages.

3. Results and Discussion

3.1. Rain Events

Plotting data for rain events at both sites provided empirical evidence of undercatch between the pit gauges and the gauges mounted above ground. Two example rain events from 2015, which occurred at the upland site, are displayed in Figure 2. The durations of the two frontal rain events shown are 42 and

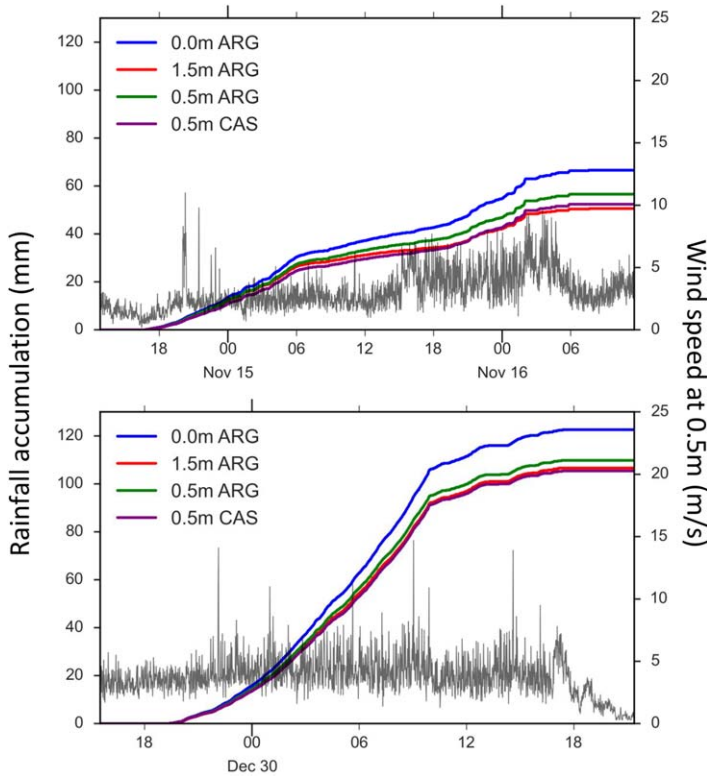


Figure 2. Time series of two storm events at the upland site showing cumulative rainfall for four rain gauges on the y axis and wind speed at 0.5 m on the secondary y axis.

28 h, respectively. The rain event in the bottom plot was named by the UKMO as Storm Frank. The duration of events selected for analysis in this study ranged between 1 and 72 h. The order of the rain gauges in terms of total accumulation remained relatively consistent, with the pit gauge (0.0 m ARG) recording the most rainfall.

3.2. Establishing the Magnitude of Differences Between Adjacent Gauges

First, the differences between two SBS-Pit gauge measurements for the lowland site were averaged over 35 concurrent rain events, and found to be 0.24 mm, or just over one tip. This shows the consistency of the SBS gauges and the calibration procedure employed. The pit gauge with the longer record of 53 storms was adopted as the reference gauge (the second SBS gauge was damaged in a bird attack, and had to be repaired and recalibrated, so was not used further as a reference gauge).

Next, we test the mean differences between the reference pit gauge and other gauges mounted above the ground for significance. The null hypothesis $H_0 : \bar{d} = 0$ was tested against the alternative hypothesis $H_1 : \bar{d} \neq 0$ where \bar{d} corresponds to $\sum d_i / N$, where d_i is the difference between the paired measurements and N is the number of rain events. A paired sample t test was used to determine if the mean of the differences between the paired observations was significantly different from zero. If the null hypothesis was not rejected, there was no statistically significant bias between two gauges.

The results of the paired sample t tests are presented in Table 2. All tests, with the exception of the 0.5 m aerodynamic SBS at the lowland site, show that the mean of the differences is significantly different

from zero at the 99.9% level. Therefore, there is strong statistical evidence that the mean of the differences between a gauge mounted above the ground and a pit gauge is different from zero. The pit gauge measurement was always subtracted from the nonpit gauge measurement, and in all cases, the mean of the differences between paired observations was less than zero. This was the expected result because a pit rain gauge is designed to minimize the effect of wind and therefore catch more rainfall than gauges mounted above the ground, but it has been proven here through statistical significance testing.

Figure 3 shows scatterplots of gauge comparisons with a simple linear regression fitted, in addition to a 1:1 line which represents complete agreement between the paired gauges. The two subplots on the top row are from the lowland site, and the three on the bottom row are from the upland site. All five subplots feature the reference pit gauge on the x axis. The regression takes the standard form $Y_t : \beta_0 + \beta_1 X_t + \varepsilon_t$ where Y_t and X_t are rainfall event totals for two gauges, β_0 and β_1 are intercept and slope coefficients, respectively, and ε_t are the random errors. Two assumptions were made concerning ε_t , that they were uncorrelated and had a Gaussian distribution with zero mean and unknown variance σ^2 (Duchon & Essenberg, 2001). Undercatch is expected by the regression model when the slope coefficient is less than one. These coefficients show that the 0.5 m mounted cylinder CAS performs least well compared to the pit gauge at both sites, followed by the 1.5 m mounted improved-aerodynamic ARG at the upland site.

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Figure 4 summarizes the distributions of CEs for the five gauges plotted in Figure 3. The vertical dashed line separates the two sites and the black horizontal line at a CE of 1.0 represents the reference measurement. At the lowland and upland sites, this reference is provided by the Pit SBS and the Pit ARG, respectively. The thick black horizontal line in the middle of each boxplot shows the median value, and the

Table 2
Results of a Paired t Test Applied to Different Combinations of Gauge

	Paired t test		
	N	$H_0 : \bar{d} = 0$	$H_1 : \bar{d} \neq 0$
<i>Gauge Pairs: Lowland Site</i>			
0.5 m SBS-Pit SBS	52	Reject	$P < 0.005$
0.5 m CAS-Pit SBS	52	Reject	$P < 0.0001$
<i>Gauge Pairs: Upland Site</i>			
0.5 m ARG-Pit ARG	83	Reject	$P < 0.0001$
0.5 m CAS-Pit ARG	61	Reject	$P < 0.0001$
1.5 m ARG-Pit ARG	83	Reject	$P < 0.0001$

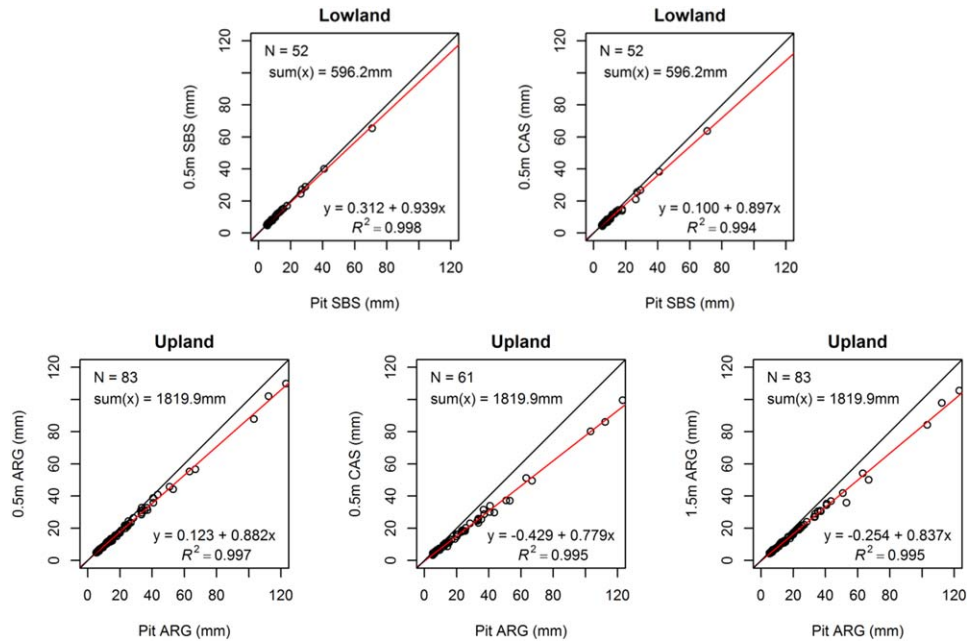


Figure 3. Comparisons of different pairs of rain gauges with the pit gauges on the x axis, with a 1:1 line (black) and the linear regression line (red) drawn.

Inter-Quartile-Range (IQR) is shown by the shaded areas. Boxplots with identical shading represent rain gauges of the same model. The IQRs of the 0.5 m mounted improved-aerodynamic gauges at both sites are closer to 1.0 than the IQRs of the conventional cylinder gauges. At the upland site, the IQR of the 0.5 m mounted ARG is closer to 1.0 than the IQR of the ARG mounted at 1.5 m.

Table 3 presents a summary of the differences between nonreference measurements paired with the pit rain gauge measurements, at both sites. Where relevant, the 95% confidence intervals for the mean differences are included, and differences greater than 10% are marked in bold. The conventional cylinder gauge mounted at 0.5 m catches 9.4% and 23.8% less than the pit gauge on average, at the lowland and upland sites, respectively. The comparable figures for the 0.5 m mounted improved-aerodynamic gauge at both sites are 3.4% and 11.2%, respectively. The maximum percentage difference was 38.5%, exhibited by the 0.5 m mounted CAS at the upland site. The implications of the results presented in Figure 4 and Table 3 are that both the mounting height and gauge shape have a greater impact on the accuracy of rainfall data than is widely appreciated.

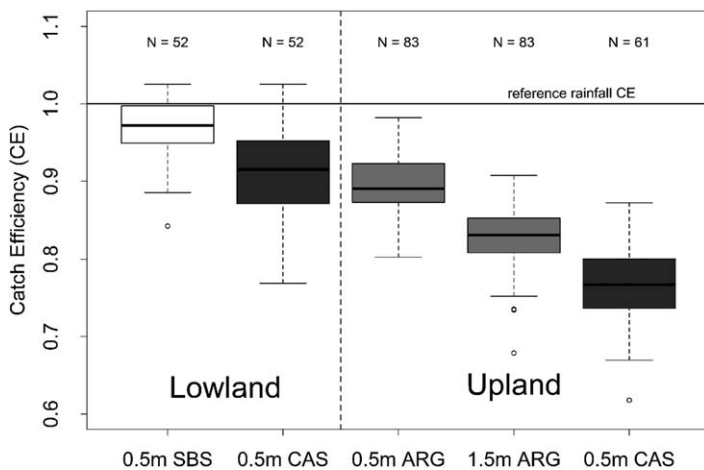


Figure 4. Catch efficiencies plotted by gauge model and mounting height for (left) lowland and (right) upland sites. The pit reference is represented by the horizontal line at CE = 1.0, for N rainfall events.

3.3. Quantifying the Wind-Induced Error

The aim of this section is to visualize and quantify the relationship between wind speeds and CE, and investigate whether it is viable to apply a multiplier to rainfall recorded by the best performing nonreference rain gauge, i.e., that with a mean CE closest to 1.0. For both sites, Figure 4 in the previous section shows that the best performing gauges were the improved-aerodynamic rain gauges mounted at 0.5 m. Therefore, the analyses in this section use the 0.5 m SBS and the 0.5 m ARG.

At this stage, it is an unproven hypothesis that the undercatch is associated with wind. However, using the same data set of N = 52 and N = 83 events, where event durations ranged between 1 and 72 h, there was no obvious relationship between CE and event-averaged wind speeds. It was presumed that an event-averaged wind statistic did not adequately represent the variability of wind during a rain event. Therefore, there is a need to examine shorter duration more homogenous periods.

Table 3
Summary of the Undercatch Exhibited by Nonreference Gauges Using the Pit Gauge as Reference at the Lowland and Upland Site, Where N are the Number of Events for Each Comparison

Gauge "Y"-Gauge 'X'	N	Mean of the absolute differences (mm)	Mean of the absolute differences: 95% confidence intervals (mm)		Mean percent error (%)	Mean percent error: 95% confidence intervals (%)		Maximum error within a rain event:		
			Lower	Upper		Lower	Upper	(i) Event size recorded by Pit (mm)	(ii) Percent (%)	(iii) Event number
<i>Lowland site</i>										
0.5 m SBS-Pit SBS	52	-0.39	-0.16	-0.62	-3.40	-1.40	-5.40	5.54	-15.78	41
0.5 m CAS-Pit SBS	52	-1.08	-0.70	-1.45	-9.39	-6.08	-12.60	8.71	-23.11	40
<i>Upland Site</i>										
0.5 m ARG-Pit ARG	83	-2.46	-1.84	-3.07	-11.20	-8.39	-14.01	15.28	-20.14	37
0.5 m CAS-Pit ARG	61	-6.03	-4.58	-7.48	-23.76	-18.04	-29.48	5.23	-38.52	43
1.5 m ARG-Pit ARG	83	-3.83	-2.98	-4.68	-17.46	-13.6	-21.33	53.06	-32.46	32

Note. Errors greater than 10% are marked in bold.

The 10 largest rain events for the upland and lowland sites were selected and split into uniform time periods, T, and the CE was calculated for each period. Due to TBR local random errors mentioned in section 2.5, a minimum interval T of 0.5 h and a minimum rainfall threshold (MRT) in each interval of 1 mm were applied, for the pit gauge. The CEs of the 0.5 m mounted improved-aerodynamic gauges for both sites were plotted against interval-averaged 1 min maximum wind speeds also measured at 0.5 m. Figure 5 shows these results for T values of 1 and 2 h. The subplots for T = 0.5 h and a MRT of 1 mm are not presented in Figure 5 because a large amount of scatter was induced by local random errors, which could not be eliminated. However, it is important to emphasize that low CEs do occur at low rainfall rates and moderate wind speeds. Moreover, rain events also occur where CE > 1, which happens more frequently with

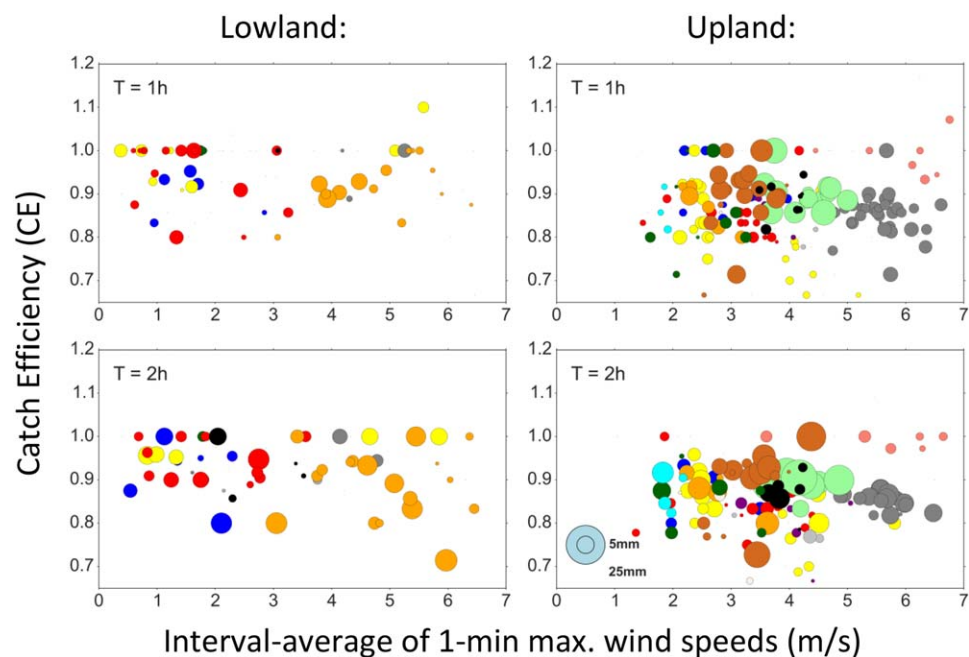


Figure 5. (left column) Plots of 0.5 m improved-aerodynamic gauge CE versus 0.5 m wind speed for lowland site and (right column) the upland site. The size of each point corresponds to the rainfall intensity, T is the interval size, and each color represents a different storm event. The minimum rainfall represented by each point is 1 mm.

shorter values of T . This supports the hypothesis whereby local random errors cause some of the differences at low rain rates, rather than the wind.

Clustering of circles of the same color are evident in Figure 5, particularly at the upland site where the largest rain events with the longest duration are identified in brown, black, and gray. However, no clear relationship between CE and averaged wind speeds is immediately evident and all subplots exhibit a large amount of scatter.

The subplots comprising Figure 5 indicate that the limits of MRT and T imposed may not be adequate to reduce sufficiently the local random quantization errors. Therefore, the MRT is increased to 2.5 mm, and the minimum value of T is set to 1 h. Moreover, a subset of the data comprising the three largest frontal rain events from the upland site, with total rainfall recorded by the pit gauge in excess of 300 mm, were selected for further analysis. Note that the largest of these three storms, Storm Frank, is plotted in section 3.1 and Figure 2 (bottom plot).

The four subplots comprising Figure 6 show the CEs for the subset plotted against the 1 min maximum wind speeds averaged over T , measured above the ground at heights of $H = 0.5$ m and $H = 2$ m. These correspond to the top and bottom rows of Figure 6, respectively. Wind speed at 2 m is plotted in order to provide a regression at the same height as most operational wind measurements, and also to examine whether a reduction in the coefficient of determination could be observed compared to the wind speed measured at 0.5 m. Also plotted are the linear regressions for $T = 1$ h (left column) and $T = 2$ h (right column).

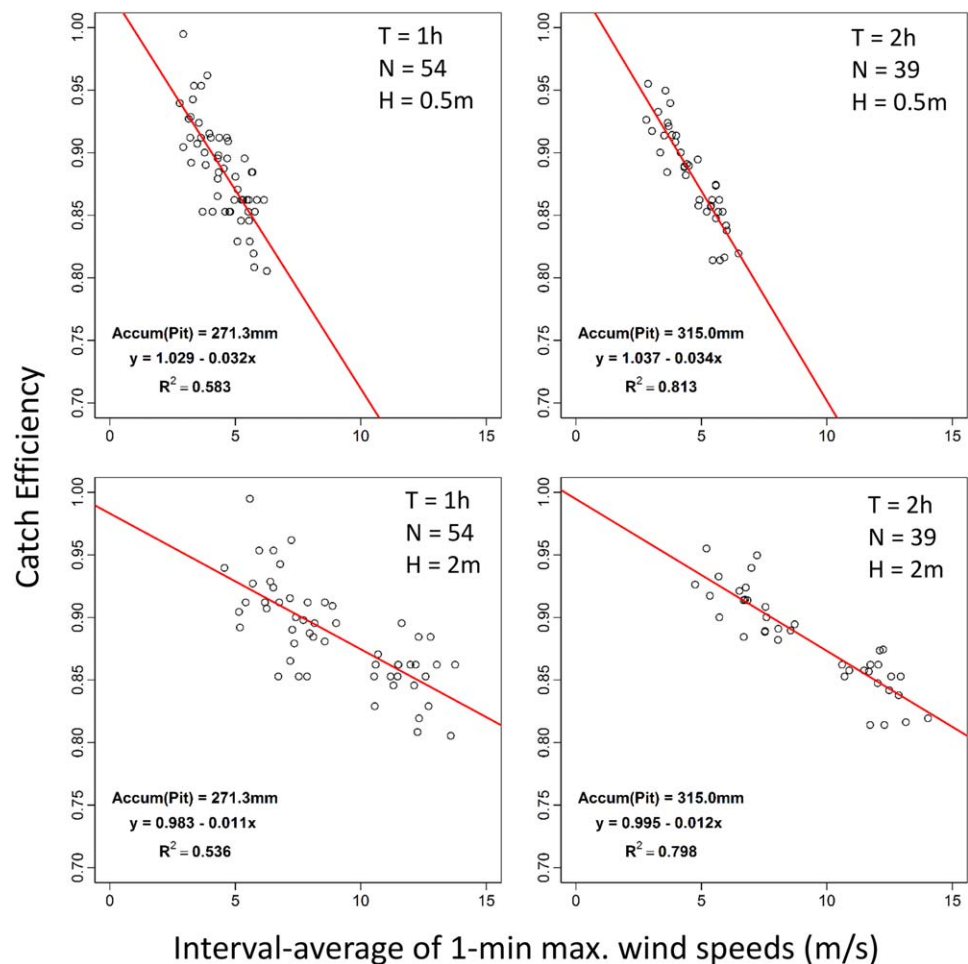


Figure 6. Scatterplots with linear regressions of CE versus the maximum wind speed averaged over T , for the 0.5 m ARG at the upland site. Wind speed measurement heights (H) plotted are (top row) $H = 0.5$ m and (bottom row) $H = 2$ m, for intervals of $T = 1$ h (left column) and $T = 2$ h (right column). N gives the number of events

column). The number of subevents of duration T is given by N . The improvement in correlation and the reduction in scatter can be seen clearly in the subplots of Figure 6, compared to Figure 5. The regression model of CE for the 0.5 m improved-aerodynamic ARG on wind speeds at 0.5 m, using $T = 2$ h, explained 81% of the variance. When the interval-averaged wind speed was 6 m/s at 0.5 m, this model predicts an undercatch of 16.7%. When T is reduced to 1 h, the explained variance of the model is reduced to 58%. For the same gauge but using 2 m wind speed, the goodness of fit was comparable but is reduced to 80% and 54%, for 2 and 1 h, respectively. All four linear regressions demonstrate evidence for statistical significance with P values < 0.0001 .

The attributes of this model are such that when 2 h accumulations from the 0.5 m mounted improved-aerodynamic ARG during large midlatitude frontal events at the upland site were between 2.6 and 21.4 mm, a linear model using wind speeds at 0.5 m predicted the undercatch to within a residual CE standard error of 0.017. However, attributing to wind speed the additional scatter exhibited by Figure 6 is complicated by a lack of information. Analysis undertaken when $MRT < 2.5$ mm was compromised by local random errors, but other factors may have contributed to the additional scatter. The averaging carried out may have partly disguised the relationship with wind speed because CE is determined by short-term wind turbulence and its characteristics. The arbitrary time-based method of sampling to 1 or 2 h may not be optimally representative of the variability of wind speeds. By identifying periods with low wind variability and splitting the rainfall into these intervals, while maintaining an appropriate MRT in each interval, the model fit may be improved. However, this would be a less practical approach. Furthermore, the drop-size distribution (DSD) affects CE because smaller and lighter rain droplets are affected more by wind than larger heavier droplets (Nešpor & Sevruk, 1999).

Next, the same subset of data were used to establish CEs for the 1.5 m improved-aerodynamic ARG and the 0.5 m mounted conventional cylinder CAS. The R^2 values for $T = 2$ h and wind speed height $H = 0.5$ m for the ARG at 1.5 m and the CAS at 0.5 m were 0.506 and 0.103, respectively. The results of these are not shown in Figure 6. For the ARG mounted at 1.5 m, it is hypothesized that the enhanced turbulence intensity created due to higher wind speeds at 1.5 m contributed to a reduced R^2 . For the CAS mounted at 0.5 m, where the wind speeds are theoretically the same as for the 0.5 m mounted ARG, it is posited that the reduction in R^2 is due to the less-aerodynamic CAS shape creating more turbulence (Colli et al., 2017). In addition, it is theorized that the local random errors described by Habib et al. (1999, 2001) and Ciach (2003) contribute to the reduced goodness of fit, particularly as these random errors may be exacerbated by the effect of the turbulence component. Moreover, the CAS has an orifice area and tipping bucket mechanism that is different to the ARG. This means that the buckets are balanced to receive a different nominal quantity of water. Therefore, tips occur at different moments in time compared to the ARG. The characteristics of the local random errors typically exhibited by the ARG may be different to the CAS. At the event-scale this is not relevant. However, for low intensity rainfall over short durations, the local random errors between two different models of TBR are likely to be greater. Therefore, comparison of the two gauges at resolutions of $T < 2$ h may not be appropriate.

For rain event durations where $T > 1$ h, the rain gauge exposure problem mainly lies in systematic components of the distorted wind flow over the gauge. Horizontal acceleration and induced upward components together contribute to the losses of incident rainfall. Turbulence is likely to have nonlinear effects on raindrop losses, which are particularly important for short duration events where $T < 1$ h. Therefore, it is critical that the role of turbulence is investigated in applications where short duration (< 1 h) rain events are important.

It was possible to improve the model fit by applying a multiple regression using rainfall intensity and temperature as additional variables. However, without further observations it was not possible to identify causes and effects. There was also the risk of parameter interaction through multicollinearity, and the loss of physical significance. Therefore, the model presented in Figure 6 using wind speed as the sole independent predictor variable over uniform time intervals was preferred because it is both simple and practical. This section demonstrates that it is viable to apply a multiplier to a 0.5 m mounted ARG during large frontal rainfall events for time intervals where the rainfall recorded by the gauge is at least 2.5 mm and the interval is at least 1 h.

4. Conclusions and Recommendations

Systematic bias caused by wind is inherent within rainfall measurements and wind is therefore the most important variable required to understand the extent of undercatch on rainfall measurements. Using a pit

gauge as a reference, this study demonstrated that rainfall measurements from an exposed upland site, recorded by an adjacent conventional cylinder rain gauge mounted at 0.5 m, were underestimated by more than 23% on average. At a well-exposed lowland site, where wind speeds were lower on average, the equivalent mean undercatch was 9.4% for the same commonly used conventional cylinder gauge.

An improved-aerodynamic shape rain gauge enhanced rainfall catch when compared to a conventional cylinder gauge shape. The mean undercatch for an improved-aerodynamic gauge mounted at 0.5 m above the ground was 11.2% at the upland site and 3.4% at the lowland site. Gauge mounting height above the ground also had a significant impact on rainfall catch, due to the vertical wind gradient. Identical improved-aerodynamic rain gauges mounted adjacent to one another at 0.5 and 1.5 m were compared at an upland site, resulting in a mean undercatch of 11.2% and 17.5%, respectively.

By selecting three large rainfall events, splitting them into intervals of uniform time duration, T , and imposing a minimum rainfall threshold (MRT) within each interval, a statistically significant ($P < 0.0001$) relationship explaining 81% of the variance was established between CE and wind speed. However, reducing T and the MRT exposed local random quantization errors, which increased the scatter and thus reduced the R^2 value.

A discrete data-recording strategy based on counting the number of tips in each 1 min was adopted in this study because it is used operationally by many NMHSs. There is an increasing requirement for high-resolution rainfall data sets (Blenkinsop et al., 2017), for example in climate research into changes in rainfall extremes (Chan et al., 2016; Lenderink et al., 2017) and urban hydrology (Ochoa-Rodriguez et al., 2015). TBR local random errors are exacerbated by a discrete data-recording strategy for low intensity rainfall over short time scales (Habib et al., 2013). For coarser resolution data (> 1 h), it may be justifiable to ignore these local random errors because they are averaged over a longer interval. However, in the context of increased demand for higher resolution rainfall products, quantification of these errors is critical. Moreover, to improve the resolution of subhourly rainfall measurements from TBRs it is a recommendation that rain gauge network operators in midlatitude regions should adapt their TBR data-recording strategy to record the time of bucket tip. This maximizes the quantity of information which can be taken from TBRs, with the user able to decide which interpolation technique to implement.

Field research undertaken in this study supports the results of CFD simulations presented by Colli et al. (2017), where the turbulence component above the orifice of a rain gauge was reported to rise nonlinearly with increasing wind speeds. Three gauges used in that study were also used in this study, with the SBS improved-aerodynamic shape exhibiting the lowest increase in turbulence with increasing wind speeds.

A general conclusion from the work conducted here is a reinforcement of the point that using an aerodynamic rain gauge is the simplest and cheapest practical way to improve rainfall collection efficiency. Despite the clear benefits of using an improved-aerodynamic profile, uptake is relatively low globally among NMHSs. The UK Met Office and the Scottish Environment Protection Agency are exceptions. Using a pit gauge is the ideal solution for measuring rainfall in situ. However, mounting a rain gauge in a pit is not a practicable solution in most cases.

The results presented herein provide a preliminary set of corrections for a 0.5 m mounted improved-aerodynamic rain gauge at a temporal resolution of 1 or 2 h based on 0.5 or 2 m wind speed. These corrections should be tested at other sites with a pit gauge, preferably using the same equipment. The corrections were developed for a well-exposed midlatitude upland site during large frontal events where hourly rainfall totals are at least 2.5 mm.

A number of improvements could be made to continue the work undertaken in this study. These are listed below in order of decreasing priority.

4.1. Measurement of Drop-Size Distribution (DSD)

It is shown that wind speed is the most important variable to measure for a correction to be applied. However, a quantitative assessment of the DSD using a disdrometer would also be useful. Alternatively, using high-resolution rainfall intensity measurements and qualitative information of the rainfall type may form the basis of a practical proxy estimation of the DSD. Further research should be undertaken to assess whether this is viable.

4.2. Measuring Near-Instantaneous Rainfall Intensity and Reducing Local Random Errors

Improving the data acquisition procedures from TBRs to accurately record rainfall intensity would facilitate assessment of the wind-induced undercatch at time scales finer than those used in this study (<1 h). This would involve recording the time of bucket tip, with rainfall measurements calculated from these using an interpolation technique, such as those presented by Wang et al. (2008), Fiser and Wilfert (2009), and Colli et al. (2013). Moreover, devices capable of measuring rainfall intensities precisely and accurately at a fine time resolution (<10 s), in particular during low rain rates, would be useful. For example, “drop-counter” rain gauges are known to demonstrate high accuracy at low rain rates and a fine time resolution (Colli et al., 2013; Norbury & White, 1971). With depth increments of these devices of the order of 0.005 mm, local random quantization errors may be significantly reduced. Furthermore, the introduction of near-instantaneous rainfall intensity (integration time <10 s) as a variable affecting the wind-induced undercatch could be investigated comprehensively.

4.3. Measurement of Wind Speed above the Rain Gauge Orifice

Recording wind speeds in 3-D above the rain gauge orifice would be an advance on the present work, while a practical compromise for further research could be to measure in 2-D. Measuring this wind speed and comparing it to surrounding concurrent wind speeds nearby to the rain gauge and at the same height above the orifice, would also provide empirical validation for the Colli et al. (2017) study.

CFD modeling and wind tunnel tests carried out interactively with ambitious field experiments, incorporating points 4.1, 4.2 and 4.3 above, may be the optimal way to make vital progress toward improved corrections for wind-induced undercatch. The CFD modeling would include optimizing of the aerodynamic profile and modeling particle trajectories, the wind tunnel testing would include introducing and tracking water droplets, while concurrent field experiments would involve similar shapes to the SBS, with larger diameter sizes.

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