Evaluating wind-induced uncertainty on rainfall measurements by means of CFD modelling and field observations

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Abstract

The most widely used device to measure rainfall is the tipping bucket rain gauge (TBR), although there is no standard design. The precision and accuracy of TBR measurements vary, and calibration procedures are dependent upon the organisation or institution operating a network. Consequently, rainfall datasets may be heterogeneous and not easily comparable. Environmental conditions at the gauge orifice also adversely influence the accuracy of measurement. The height at which the gauge is mounted has a significant influence on the gauge catch. Reference measurements can be made using a rain gauge in a pit structure, with the gauge orifice positioned at ground level. Different types of rainfall events, occurring in differing geographical and micro-topographical contexts, vary the influence of the wind on rainfall measurement. Hence, it is difficult to develop and apply an all-encompassing correction procedure for wind using empirical observational methods alone. Computational Fluid Dynamics (CFD) provides an ideal framework within which to develop an understanding of how wind affects catch accuracy. Observational data from the field can be used to validate CFD simulations and enhance correction algorithms.

1. Introduction

From Jevons (1861) to Strangeways (2004), much has been written about the rainfall measurement problem, and a lot of the focus gravitated towards the environmental impact of the wind's influence on rainfall catch. Scientific consensus dictates that the physical presence of a rain gauge causes an acceleration of the airflow over the orifice, distorting the trajectories of rainfall particles and leading to an 'undercatching' effect. Additionally, the shape of the rain gauge has an influence on the catch performance. Despite numerous intercomparison studies, the rainfall undercatch problem remains unresolved. Studies such as those by Sevruk and Hamon (1984), Goodison, Louie and Yang (1997) and Nespor and Sevruk (1999) significantly advanced knowledge and succeeded in raising further research questions, but the complexity involved ensures the solution to this problem remains elusive.

The WMO laboratory (2005) and field (2007-2009) intercomparisons on rainfall intensity took the necessary step of linking the meteorological and metrological communities, moving the science in the direction of operational standardisation. These studies have contributed to improvements in measurement over the last decade, particularly with regards to TBR counting errors. Now, the wind issue is coming back into focus once again, for example Wolff et al. (2015) and Colli et al. (2015).

2. Methods

The experimental design of this project aims to use field data from empirical observations to support theoretical analysis conducted in the context of Computational Fluid Dynamics (CFD) simulations. It is hoped that the results produced by both methods will converge to improve the understanding of the aerodynamic influence of gauge shape on rainfall catch.

<u>Field observation data</u>

A detailed rainfall experiment is set out to understand wind-induced undercatch (Pollock et al. 2014). Four UK sites are instrumented, representing lowland, upland, westerly and easterly rainfall regimes, Figure 1. Conventional knowledge describes how prevailing winds in the UK blow from the west/south-west. These winds whip up moisture from the Atlantic and the Irish Sea, delivering it as orographic enhanced rainfall along the UK's west coast. Wilkinson (2009) describes the difficulty of 'closing' the water balance in Cumbria, western England, due to the impact of undercatch. Two sites in the west of the country were selected to capture this prevailing UK weather pattern, one site representative of the lowlands and one of the uplands. The significance of this lies in the varying level of exposure to the wind across the UK's undulating terrain. Convective rainfall events are more common in the east of the UK, particularly in the summer months. Again, an upland and a lowland site are selected to represent the eastern rainfall regime.

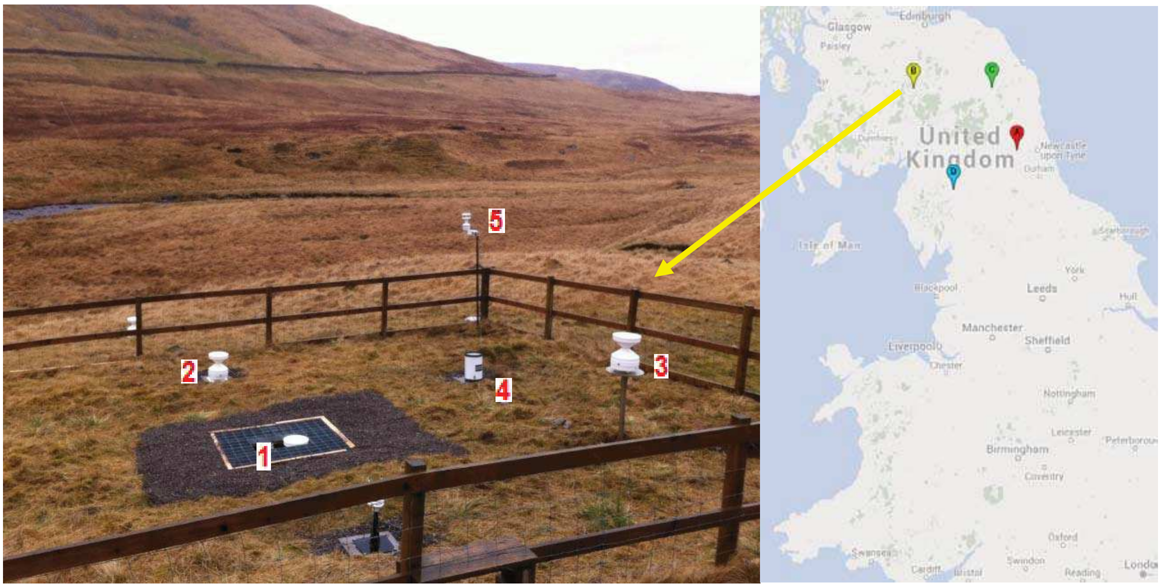

Fig 1: Talla Reservoir research station, Scottish Borders. Elevation: 430m. Identical aerodynamic rain gauges (ARG100s) are mounted at different heights: reference pit gauge (1), ground-mounted gauge (2), 1-metre mounted gauge (3). There is also a ground mounted straight-sided gauge (4) and wind speed measurement at two metres (5) This upland site is situated at the top of a valley running east-west, with strong winds observed. (Picture by M.Pollock, April 2015. Site provided by University of Dundee).

<u>CFD modelling of precipitation gauges</u>

CFD is used to model the airflow over the rain gauge orifice and study the effects. Recent studies have demonstrated that modelled collection efficiencies agree well with field measurements for snowfall. Variations in the precipitation characteristics (particle size distribution and precipitation type) helps explain a large part of the collection efficiency variability generally observed in field investigations (Colli et. al., 2015).

CFD provides a flexible framework which is capable of generating a wide variety of wind regimes. High resolution three dimensional wind measurements from field observations are used to compute the turbulence intensity boundary conditions according to the mean wind speed magnitude. A constant vertical profile of the wind is assumed to simulate time averaged fields such as vector air velocity and turbulent kinetic energy. A finite volume technique is implemented by solving Reynolds-Averaged Navier Stokes equations, using the SST k-Omega model. The effect of gauge shape on the aerodynamic response is investigated by modeling different gauge geometries. Gauge profiles designed on the basis of empirical evidence to decrease the air resistance (Strangeways, 2004) are compared against conventional cylindrical-shaped gauges, and the effect on wind speed and turbulence is studied.

3. Results

A subset of the field data collected at the upland/western research station, Talla Reservoir, are analysed in this section. Two rainfall events are selected, with different wind characteristics, for analysis. CFD model simulations are also presented, explaining the physical basis for the results observed in the field data visualisations.

Field observation data

Data plotted in Figure 2 show the cumulative totals for two rainfall events at Talla Reservoir. These events are observed to be typical for this site. Event (A) is characterised as a low wind event and (B) is classified as a high wind event. Cumulative rainfall totals are provided for (1) a pit gauge, (2) a ground mounted aerodynamic gauge, (3) a pedestal mounted (1m) aerodynamic gauge and (4) a ground mounted straight-sided gauge. In both events the pit gauge records consistently the highest amount of rainfall. The ratio of the ground mounted aerodynamic rain gauge to the pit was 0.91 and 0.93 for events (A) and (B), respectively. In contrast the 1m mounted aerodynamic gauge's equivalent ratios were 0.84 and 0.83. Of particular interest is that the pedestal mounted aerodynamic gauge registers a very similar collection efficiency to the straight-sided gauge at ground level.

The same trend is also observed when the cumulative data is plotted over spring and summer periods, as shown in Figure 3. If the pit gauge measurement is assumed to be the “truth”, the 1-metre mounted aerodynamic gauge and the comparable ground mounted straight-sided gauge are deficient by between 17 – 20% across the time intervals selected.

CFD modelling of precipitation gauges

The two types of rain gauge used in the field study at Talla Reservoir are modelled using CFD, and visualisations of their aerodynamic performance are presented in Figure 4.

The plots are presented as vertical pairs to allow a direct vertical comparison between the different shapes. The ARG100 aerodynamic rain gauge is presented along the top row (1a – 3a), and a conventional straight-sided gauge is displayed along the bottom row of the figure (1b – 3b). The magnitude of velocity U_m represented on a stream-wise vertical plane for the two gauges (1a-1b) confirms the presence of a shear layer (white band). This separates the region characterised by strong airflow regimes above the collector ($U_w < U_m$, red colour), from the recirculating airflow inside the gauge ($U_w > U_m$, blue colour). In the case of the ARG100 this shear layer spans over the orifice and touches the downwind rim of the collector, whereas in the case of the straight-sided gauge it develops far beyond the downwind edge of the collector and reaches higher vertical levels. This behaviour is partially explained by the stronger downdraft occurring inside the ARG100 collector (Figure 2a-2b). The straight-sided gauge shape also causes higher turbulent kinetic energy values just above the collector (Figure 3a-3b), demonstrating an improved aerodynamic behaviour of the ARG100. The actual implications of this evidence on the rainfall trajectories should be evaluated by coupling the CFD airflows with Lagrangian particle tracking models.

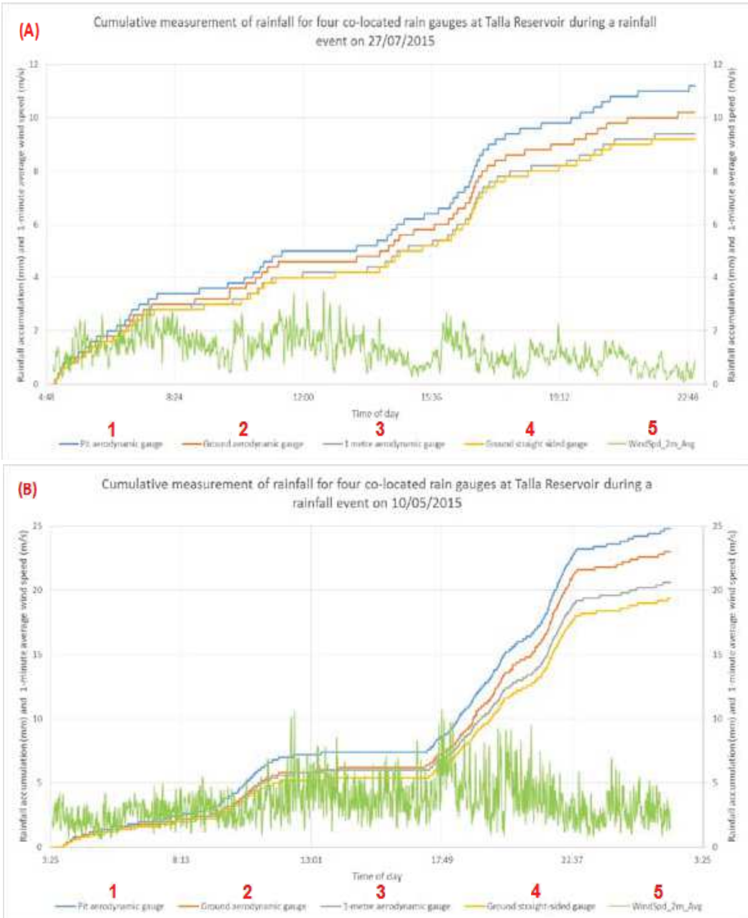

Fig 2: Two events from Talla Reservoir research station. (A) is a rainfall event where wind speeds ranging from 0-3 m/s. (B) is a rainfall events where wind speeds range from 1-11 m/s. The cumulative totals (mm) of rain gauges mounted at different heights are plotted.

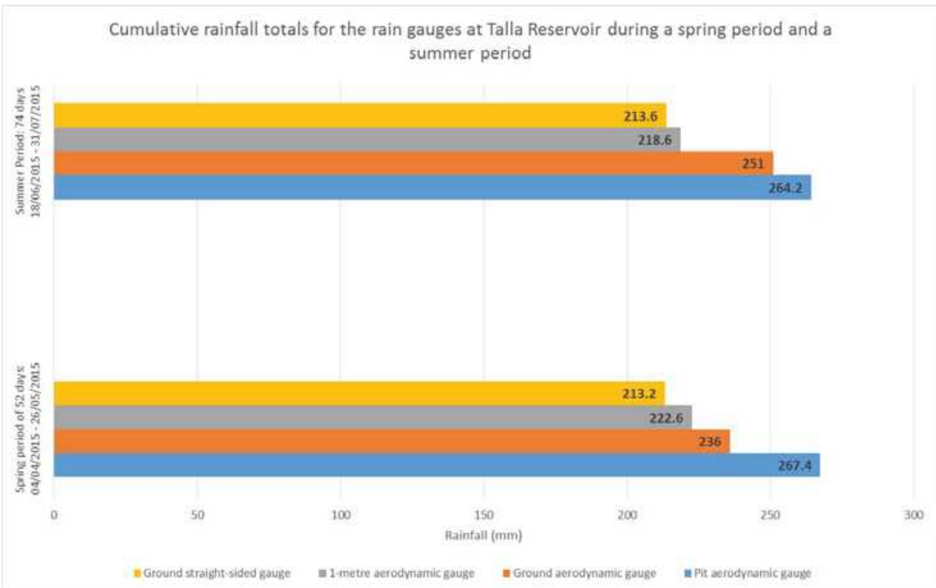

Fig 3: Cumulative rainfall totals for the four chosen rain gauges, covering a spring period lasting 52 days and a summer period lasting 74 days.

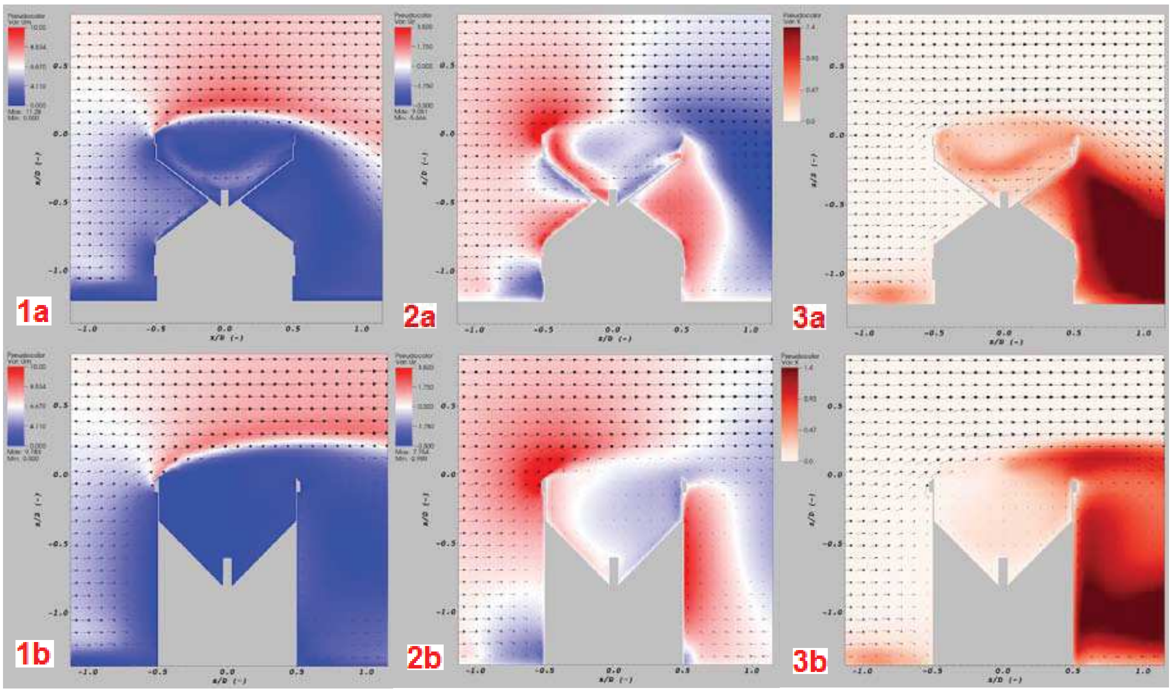

Fig 4: CFD visualisations of the stream-wise vertical view of different parameters, for wind speeds of 7m/s. The figures are displayed as pairs, with the aerodynamic profile of the ARG100 on the top row (1a, 2a and 3a), and the conventional straight-sided gauge shown on the bottom row (1b, 2b, and 3b). 1a and 1b show the air velocity magnitude colour Um (m/s) plot and vector plot of the airflow. 2a and 2b show the air vertical velocity component Uz (m/s) plot and vector plot of the airflow. 3a and 3b show the turbulent kinetic energy k (m2s-2) plot and vector plot of the airflow.

4. Conclusions and recommendations

The CFD study shows that the shape of the rain gauge is significant when considering catch efficiency. The aerodynamic shape of the ARG100 is less affected by turbulence than the conventional straight-sided gauge. Data from the field site at Talla Reservoir supported this assumption because the rain gauge in the reference pit consistently recorded more rainfall than other co-located rain gauges mounted at different heights.

Work is still to be undertaken to explain the undercatch issue more clearly before attempting to resolve it. There are also other considerations such as the influence of the drop size distribution, intensity, and how the characteristics of a site's macro and micro topography, influence rainfall measurement accuracy. Furthermore, new European (CEN) calibration standards soon to be published will improve the interoperability of rainfall measurements. It will be interesting to see how applying a retrospective calibration coefficient to TBRs will influence datasets. Future work will include this goal. Deeper analysis of the observational data is needed to better understand the phenomenon of wind-induced undercatching. CFD simulations aimed at predicting rainfall particle trajectories using the Langrangian tracking model is recommended. This method has already been tested and optimised for solid precipitation measurements by Colli et al. (2015).

References

Colli, M., R. Rasmussen, J. M. Theriault, L. G. Lanza, C. B. Baker & J. Kochendorfer (2015) An Improved Trajectory Model to Evaluate the Collection Performance of Snow Gauges. *Journal of Applied Meteorology and Climatology,* 54**,** 1826-1836.

Goodison, B., P. Louie & D. Yang (1997) The WMO solid precipitation measurement intercomparison. *World Meteorological Organization-Publications-WMO TD***,** 65-70.

Jevons, W. S. 1861. On the deficiency of rain in an elevated raingauge as caused by wind. In *London, Edinburgh and Dublin Phil. Mag*, 421–433.

Nespor, V. and Sevruk, B. (1999). Estimation of wind-induced error of rainfall gauge measurements using a numerical simulation. J. Atmos. Ocean. Tech, 16(4), 450-464.

Pollock, M., M. Dutton, P. Quinn, P. E. O'Connell, M. Wilkinson & M. Colli (2014) Accurate Rainfall Measurement: The Neglected Achilles Heel of Hydro-Meteorology

Sevruk, B. & W. Hamon. (1984). *International comparison of national precipitation gauges with a reference pit gauge*. Secretariat of the World Meteorological Organization.

Strangeways, I. (2004) Improving precipitation measurement. *International Journal of Climatology,* 24**,** 1443-1460.

Wilkinson, M. E. 2009. A multiscale nested experiment for understanding and prediction of high rainfall and flood response spatial behaviour in the Eden Catchment, Cumbria, UK. Newcastle University.

Wolff, M. A., K. Isaksen, A. Petersen-Overleir, K. Odemark, T. Reitan & R. Braekkan (2015) Derivation of a new continuous adjustment function for correcting wind-induced loss of solid precipitation: results of a Norwegian field study. *Hydrology and Earth System Sciences,* 19**,** 951-967.