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Evaluation of Tipping Bucket Rain Gauge Performance and Data Quality

Science Report: W6-084/SR



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AGENCY**

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Professor Mike Depledge Head of Science

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EXECUTIVE SUMMARY

This report covers four key areas:

1. An in depth literature review of the issues and problems pertaining to the use of tipping bucket raingauges (TBRs)
2. A survey of current Environment Agency practice pertaining to the use of TBRs.
3. Laboratory testing of 8 types of TBR to determine the best method for calibration and compare gauge reliability and accuracy
4. Field evaluation of 8 types of TBR to assess, reliability in the field, relative performance in terms of catch compared to the standard Meteorological Office 5"

The need for the work arose from the fact that the Environment Agency routinely collects rainfall data for flood risk prediction, flood warning and water resource planning activities. Discrepancies between the records obtained from tipping bucket raingauges (TBRs) and conventional storage gauges. The problem that has been identified, namely under-recording by TBRs, has particular implications for work relating to water resources since, whilst the error may be relatively small on any one event, the significance may increase as rainfall totals are accumulated over longer periods.

The literature review found general agreement among the authors of the papers reviewed that one of the most important factors affecting raingauge performance is exposure to wind and that the effect increases with height of the gauge rim above the ground surface. Evidence was found in the literature that use of gauges with an aerodynamic shape (champagne glass) were measurably better than standard shapes (cylindrical). The other most important effect identified in the literature reviewed relates to the relationship between TBR calibration error and rainfall rate. This was reported to be most marked during heavy rainfall, when water flowing in to the buckets while they are tipping can represent an error of up to 10 – 30% compared to a co-located storage gauge.

The laboratory investigations compared the two methods, constant rate and burette, currently used by the Environment Agency for calibration of TBRs. It was concluded that constant rate method should provide a calibration coefficient that is more robust at higher intensities than one measured by the burette method. It was also concluded that gauges calibrated by the constant rate method will underestimate at higher rainfall intensities and better precision could be obtained by use of a full dynamic calibration (i.e. calibration at a number of rates).

The influence of temperature on the calibration methods themselves was concluded to be small and can be corrected for if required. The calibration coefficient of tipping bucket rain gauges varies with temperature although in most gauges the change were found to be small. The frequency at which gauges were found to need calibration was annual in general although biannual calibration might be beneficial in high rainfall areas.

Field testing of the gauges was undertaken at an experimental site located at Eskdalemuir Observatory in Dumfries and Galloway, which is situated in the Southern

Uplands of Scotland. The National Grid Reference of the site is NT 32356026 and the station is located at an altitude of 242 m. Long-term average annual rainfall for the site is 1567mm. Eight different types of tipping bucket rain gauge were tested by comparison against a control gauge (meteorological office 5" gauge read daily) at a vertical height of 12". To allow greater experimental robustness, three of each gauge type were deployed, making a total of 24 TBR gauges at the test site. Supplementary control data were obtained from 2 extra meteorological office 5" gauges ; one pit mounted and one behind a turf wall.

Under the conditions encountered at the study site it was found that a TBR caught at least 5% rainfall less than a standard meteorological office 5" gauge and that under reading could be as large as ca. 20% with the worst performing gauges. Under the conditions encountered at the study site considerable differences in rainfall catch were observed between different types of TBR. A key finding was that under the conditions encountered at the study site an aerodynamic gauge achieved the catch that was closest to a standard meteorological office 5" gauge. No definitive link could be shown between variations in either temperature or wind speed and the rainfall catch of a specific gauge although on a qualitative basis the results suggest that there is a seasonal link, with a 4-5 % reduction in TBR catch (for all gauge types) observed in the winter months. Due to the low rainfall intensities encountered at the study site implementation of a correction using dynamic calibration did not significantly increase measured catch although benefits may well be obtained at other sites.

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1 INTRODUCTION

The Environment Agency routinely collects hydrometric data for flood risk prediction, flood warning and water resource planning activities. As part of this work they have identified discrepancies between the records obtained from tipping bucket raingauges (TBRs) and conventional storage gauges. The problem that has been identified, namely under-recording by TBRs, has particular implications for work relating to water resources since, whilst the error may be relatively small on any one event, the significance may increase as rainfall totals are accumulated over longer periods.

Work is needed to determine whether the discrepancy between the two systems is systematic and can be linked to specific factors, or occurs randomly. If the error is systematic, and is linked to some specific variable, data correction may be possible. The environmental factors that are likely to be most critical are rainfall intensity, wind speed and raindrop size although temperature may also play a part. Raingauges supplied by different manufacturers may perform differently and performance may also change with time, depending for example, on the robustness of the equipment and the environmental conditions under which it is used. Calibration of gauges is thus also a key issue relating to data quality. Variation between different types of dataloggers used to collect and store the data is considered less likely to be a contributing factor, given reliable supporting programming. However, detection of false signals due to inductive effects in the cable connecting the gauges to the logger can occur. For example, spurious rainfall data have been detected which were traced to the effect of an electric cattle fence running parallel to the data collection cable.

2 METHODOLOGY

This section describes the overall approach used in each of the sections, however, the detailed methodologies pertaining to individual tests will be found in the specific chapters relating to this topic area

2.1 Literature Review

The objective of the review was to provide a synopsis of the most recent International publications addressing TBR deployment, data quality, calibration methodology and measurement errors. The approach used was to evaluate all publications with relevant keywords cited on the Key databases DIALOG, CAB etc and thus identify all relevant references published within the last twenty years. All known UK manufacturers of meteorological equipment were contacted and asked to contribute any relevant in-house publications to the review. The review also made use of available information from International standards pertaining to the use of raingauges. Data was also sourced relating to comparative trials of raingauges undertaken by the UK Meteorological office, for which purpose a member of its staff was retained as a project consultant.

2.2 Laboratory Testing of Gauges

Eight different patterns of TBR were tested covering a wide range of materials, shapes and cost. The work in this area focussed on a number of specific key issues:

1. To determine whether there are specific advantages in calibrating tipping bucket rain gauges using either:
 - a. the burette method
 - b. the constant rate method (or one point dynamic calibration method)
 - c. the full dynamic calibration method
2. To determine the influence of the temperature at which calibration is undertaken and rainfall intensity.
3. To determine the long-term reliability of different makes of tipping bucket rain gauge
4. To identify specific operational problems relating to specific makes of tipping bucket raingauges.

2.3 Field Testing of TBR gauges

A field trial was undertaken at Eskdalemuir observatory with the objective of comparing in the field the relative performance of the same 8 different patterns tipping bucket rain gauges evaluated in the laboratory. The specific objectives were to look at:

- (a) Reliability in the field
- (b) How the "rainfall catch" as measured by the TBRs compares to that achieved by a standard Meteorological Office 5" gauge.
- (c) How rainfall intensity and wind speed interact with the rainfall catch obtained from different designs of tipping bucket rain gauge.

3 LITERATURE REVIEW

3.1 Objective

To compile a synopsis of the most recent international publications addressing Tipping Bucket Raingauge deployment, data quality, and calibration methodology and measurement errors.

3.2 Introduction

The Tipping Bucket Raingauge (TBR) is widely cited as having been invented as long ago as the seventeenth century by Sir Christopher Wren (e.g. Biswas 1970). In the intervening years the TBR has been extensively refined, and is now one of the most popular recording raingauges in use by many national weather agencies. Although the basic principle of individual gauge designs are similar, there is no international standard, and many different models are in use nationally and internationally which may vary in materials and design. Guidelines for the siting and use of raingauges are produced by individual national meteorological offices, and also by the World Meteorological Organisation (WMO). In the UK, in addition to the Meteorological Office guidelines, there is a British Standard (BS 7843) covering all aspects of raingauge use. A number of these recommendations/guidelines are incorporated in the relevant sections of the Environment Agency's Hydrometric Manual.

The advantages of TBRs are well known, and have been reported extensively. For instance, Smoot (1971) and Linsley (1973) reported on their high accuracy in recording low-to-intermediate intensity rainfalls, reliability and suitability for remote recording. Conversely, researchers have also been aware of potential recording problems for an equally long period. Problems with under-recording when compared with a storage gauge are identified in the UK Meteorological Office handbook of meteorological instruments as early as the 1956 edition. Under-recording during high-intensity rainfall events was reported by Bruce and Clark (1966), and the use of calibration methods to remedy this problem by Smoot (1971).

Other possible recording inaccuracies are common to all raingauges, including TBRs, and include those due to location (aspect and exposure), especially wind effects, which were extensively reported by Robinson and Rodda (1969).

This report seeks to give an overview of recent (<20 years) published research into the use of the TBR and alternative automatic gauges, including aspects of data quality and calibration. The information presented will be applied to the wider review of TBR laboratory and field performance being undertaken by the Environment Agency. Reviews of published papers are given in chronological order under each section.

3.3 Tipping Bucket Raingauge Errors and Calibration

3.3.1 Non-specific TBR errors

Errors due to site and exposure common to both storage and recording gauges.

Folland (1988) Reviewed the problem of raingauge exposure (to wind effects) and developed a quantitative theory of raingauge exposure. He considered wind flow over

the orifice of a standard 5 inch raingauge using wind tunnel data published by Robinson and Rodda (1969) and Helliwell and Green (1974). The resulting model was integrated for a range of raindrop sizes and frequency distributions after Ulbrich (1983) to give a range of curves describing the percentage of rainfall lost at given wind speeds and rainfall characteristics. The calculated results compared well to observed losses under UK conditions, using ground level gauges as a reference. He also suggested a new design of raingauge (“flat champagne glass gauge”) which aimed to substantially lower the systematic losses of rainfall volume in the high winds commonly found over exposed areas of land.

World Meteorological Organisation (1994) Emphasises the importance of site selection, especially in having all gauges within a given area subject to the same siting criteria. The suggested aim would be to choose a site to give the minimum possible wind speed over the gauge orifice, without blocking precipitation by surrounding objects. Sites subject to turbulent wind, including sloping sites and those with windbreaks, should be avoided, although some uniform shelter from all directions is desirable. The recommended method of reducing exposure where natural shelter is not available is to install the gauge in a pit, or slightly less effective, within a circular turf wall of radius 1.5m. An alternative solution was to fit a windshield around the instrument. WMO estimate loss of catch due to wind effects in the range 2-10% of the actual rainfall. Other errors considered include wetting losses from internal walls of collectors and measuring containers (2-10% loss), and loss from evaporation (0-4% loss). A number of correction factors for different wind speeds are given.

BS 7843 2.1 (1996) Identifies over-exposure (to wind) as the most important factor contributing to loss of catch by all raingauges. As the wind speed is known to increase with height above the ground surface, the recommended method of reducing wind effects is by mounting the raingauge in a pit with the collecting rim at ground surface. This method can increase rainfall catch at lowland sites by 3% to 6%, and at windy upland sites by up to 20% compared to a standard above-ground gauge. Other suggested methods of reducing errors due to exposure include the construction of a turf wall round the gauge to the height of the collection rim, at a distance of five times the gauge height. The use of wind breaks, or the use of natural hollows are also considered acceptable, although objects with an angle of elevation over 26.5° from a gauge location will lead to over-sheltering, and reduced rainfall catch.

Seibert et al. (1999) Sought to reduce systematic errors due to aerodynamic effects and wetting losses known to bias point measurements of precipitation. In the NOPEX project a rain gauge with a new type of windshield and a special weighing construction was used to minimize these errors. The windshield consisted of a flange surrounding the gauge at the level of the orifice. The idea was to screen the area above the orifice from the disturbance of the wind field by the gauge. At different locations the measured precipitation amounts were compared with the amounts caught by standard gauges. The analysis showed that the catch of the new gauge was higher than that of the standard gauges. A difference of about 3% was related to reduced wind-induced losses, while a difference of about 0.25 mm per event was explained as elimination of wetting loss. At one location the differences were related to wind speed and rainfall intensity to evaluate the effect of the windshield. The relative differences were largest (20%) for events with low intensity and high wind speed.

3.3.2 Solid precipitation

Goodison and Louie (1985) Describe the use of a snowgauge to measure the water equivalent of snowfall in Canada, where one third of the mean precipitation for the country occurs as snow. The Canadian Nipher shielded snowgauge gave an average catch within 10% of the ground true (determined using snow boards) at wind speeds of up to 5.5 ms^{-1} .

WMO (1994) and BS 7843 2.1 (1996) Both identify that raingauge exposure errors are magnified when measuring snowfall, where an error in the range 10-50% of actual deposition can be expected. Sources of error include “Blow out” in low temperatures where small snow particles are sucked out of the collector by wind eddies above the collector. “Blow in” when drifting of snow occurs, and burial in major snow events. Problems other than exposure effects include “arching” when snow adheres to the funnel rim and bridges the gauge orifice when temperatures are close to melting. And “over topping” of the gauge. Specialized snow gauges designed to melt snow in the collector are much more effective, although are rarely used in the UK.

3.3.3 Errors specific to TBRs and calibration techniques

Calder and Kidd (1978) considered that the dynamic calibration of TBRs was required to achieve both high resolution and accuracy. They state that in general, a non-linear relation exists between flow rate and the tipping rate of a tipping-bucket gauge. Other methods have been used either to avoid or correct for this non-linearity, including the use of a siphon incorporated between receiver and bucket which is designed to empty at a constant flow rate into the bucket. The method proposed in this report was to determine the gauge parameters V and t by measuring the tipping rate of the bucket at known flow rates. If T , the time between tips, is plotted graphically against the reciprocal of the flow rate, the volume of the bucket (V) is given by the slope of the line, and the tipping time (t) is given by the intercept on the T - axis. Graphs were produced to show the typical calibration results of a 1.2-l, tipping-bucket flowmeter and of a 0.1-mm, tipping-bucket raingauge. These calibrations showed that the tipping time did not change significantly either with different gauges of the same type or with moderate adjustments to the volume of the gauge. This result was important because it allows an individual dynamic calibration to be obtained from one determination of T at a given flow rate.

Adami and Da Deppo (1986) Investigated systematic errors associated with TBRs. The research focused on the accuracy of the tools used for operational use by the National Hydrological Service of the Italian Ministry of Works. Positive errors (to 2-3%) were shown at intensities lower than the calibration standard of 60 mm/hr and negative errors (to 7%) were seen at higher intensities. Non-negligible sources of error, other than those referring to external effects of wind, splashing, wetting, evaporation and blowing snow, are singled out, e.g., horizontal misalignments or poor upkeep. A new type of weight pluviograph (raingauge) aimed at overriding the mentioned shortcomings was conceived and developed. A brief description of the structure of the instrument was given, including the details of the collecting mouth and the electronic scaling. The foremost feature of the tool, which can be inserted at ease within centralized data acquisition systems, lies in its high sensitivity in recording very intense precipitation.

Niemczynowicz (1986) Carried out the dynamic calibration of three types of TBR in use in the Nordic countries (the LTH, PLUMATIC and RIMCO gauges). It was found in all

gauges tested that the volume of water required to tip the bucket was not a constant characteristic for the gauge but depended upon rainfall intensity. Thus, to avoid errors, a calculation of the rainfall intensity or of rainfall volume from tipping bucket registrations must go through an empirical, usually non-linear calibration function. The procedure involved in the dynamic calibration of the tipping bucket rain gauges is described. Examples of typical calibration curves are provided. The magnitude of errors, with regard to measured rainfall intensity, which occur when linear gauge calibration is used ranged from 2% across the measuring range for the RIMCO gauge (siphon system delivers constant flow to bucket) to 10% at 5 mm min^{-1} for the PLUMATIC raingauge.

Hsu Sheng (1990) Tested the rainfall rate error associated with a TBR under various rainfall intensities. It was found that the rate-error could be as large as a 35% underestimation of the actual rainfall amount at an upper measurable limit of the gauge, and close to 8% for less extreme events. However, if a laboratory-based regression equation was applied to normalize the rate-error on each of 10-minute records, the error of underestimation could be reduced to as low as 0.8%. Other possible errors were observed in the laboratory. These were generally small, and difficult to quantify. They included surface tension effects, and the time taken for the bucket to drain totally. It was estimated that these effects would amount to no more than 2% of the rate error.

Simic and Maksimovic (1994) Considered the dynamic characteristics of using a siphon that can be applied to control the movement of rainwater from the collecting funnel of a raingauge to the compartments of the tipping bucket. Since commercially available tipping bucket raingauges suffer from non-linearity, a modified siphon was developed. The dimensions of its elements were designed to meet linearity requirements up to a certain maximum rainfall intensity. The modified raingauge was shown to achieve linearity for the chosen range of intensities.

Humphrey et al. (1997) developed an automated method for the dynamic calibration of TBRs. The system consisted of a programmable pump, datalogger, digital balance, and computer. Calibration was performed in two steps: 1) pump calibration and 2) rain gauge calibration. Pump calibration ensures precise control of water flow rates delivered to the rain gauge funnel; rain gauge calibration ensures precise conversion of bucket tip times to actual rainfall rates. Calibration of the pump and one rain gauge for 10 selected pump rates typically requires about 8 h. Data files generated during rain gauge calibration were used to compute rainfall intensities and amounts from a record of bucket tip times collected in the field. The system was tested using 5 types of commercial TBRs (15.2-, 20.3-, and 30.5-cm diameters; 0.1-, 0.2-, and 1.0-mm resolutions) and using 14 TBRs of a single type (20.3-cm diameter; 0.1-mm resolution). Ten pump rates ranging from 3 to 154 ml min^{-1} were used to calibrate the TBRs and represented rainfall rates between 6 and 254 mm h^{-1} depending on the rain gauge diameter. All pump calibration results were very linear with R^2 values greater than 0.99. All rain gauges exhibited large non-linear underestimation errors (between 5% and 29%) that decreased with increasing rain gauge resolution and increased with increasing rainfall rate, especially for rates greater than 50 mm h^{-1} . Calibration curves of bucket tip time against the reciprocal of the true pump rate for all rain gauges also were linear with R^2 values of 0.99. Calibration data for the 14 rain gauges of the same type were very similar. The developed system can calibrate TBRs efficiently, accurately, and virtually unattended and could be modified for use with other rain gauge designs.

3.4 Tipping Bucket Raingauge Construction and Use

Cornish and Green (1981) Constructed a TBR from mainly plastic materials more economically than the equivalent commercially available gauges. Over a two month trial, 24 h rainfall of 1-69 mm was recorded with an accuracy of 2% when compared to a storage gauge.

Hughes, Strangeways and Roberts (1993) tested a prototype “champagne glass” and a production model “cone” gauge. He found that these “aerodynamic” models had the capacity to improve rainfall catch, and could be exposed well above ground in windy conditions while still giving reasonable results.

Hanna (1995) Notes that there was to date no international agreement for raingauge design, only a compromise in the form of the World Meteorological Organisation (WMO) Interim Reference Precipitation Gauge which was considered to be markedly different from most national gauge designs. The author suggests that wind turbulence is likely to statistically outweigh any instrumental errors that may be specific to the TBR, and that special importance must be attached to more rigorous and quantitative rather than qualitative site selection. As windshields were considered to be demonstrably of limited use, a certain amount of natural shielding was suggested to be preferable. Apart from the wind turbulence problem, reduction of the discrete sampling error of the TBR was discussed. While there was as yet no absolute standard for rainfall measurement, there was clearly a need to standardise a suitably effective and practical type of TBR. The Weighing Tipping Bucket Raingauge (WTBR), a direct-rate measuring instrument, was believed to offer the greatest future potential once practical versions could be more widely implemented, while taking care to maintain historical continuity of precipitation records.

Hellin and Haigh (1998) Reported the performance of a TBR located in southern Honduras during Hurricane Mitch. The Gauge recorded 698mm in a 41 hour period, with peak rates approaching 60mm h⁻¹.

3.5 Tipping Bucket Raingauge Data Manipulation and Comparison of Data Sets

Maksimovic, Buzek and Petrovic (1991) Presented a methodology for correcting TBR data to take account of non-linearity in rainfall catch at differing rainfall intensities. They also investigated errors due to “double tipping” and bucket volume, and suggested corrections.

Sevruk (1996) Compares the 6-year mean annual difference in precipitation values as measured using the Hellmann (storage) gauge and the tipping-bucket recording precipitation gauge at the same open site at the Airport of Geneva. The tipping-bucket gauge was shown to record less precipitation by a mean of 14%. The percentage differences in daily precipitation amounts depended on wind speed and intensity of precipitation. The non-linear prediction model developed from these data was based on 576 daily values during the period 1980-1985, and showed that there was a threshold value of precipitation intensity for each interval of wind speed. This threshold value increases with increasing wind speed. Below the threshold value a sharp increase in percentage difference exists with decreasing intensity. It was suggested that

relationships of a similar nature could have a general application for corrections of the wind-induced error of precipitation measurement or for adjustments of precipitation values from one gauge type to the other

Yu et al. (1997) Discuss discrete sampling errors when using TBRs to develop infiltration – time relationships in small catchments. An analytic expression was derived for sampling errors associated with a constant rainfall intensity or runoff rate. The analytic results were then generalized to include real precipitation events when both rainfall intensity and runoff rate are highly variable. The implications on equipment design and assessment of model performance were considered.

3.6 Comparison of TBR Types

Marsalek (1981) Carried out laboratory calibrations on three TBRs available in Canada. – The Canadian Atmospheric Environment Service TBR, The Stevens TBR (Leupold and Stevens Inc) and Texas Electronics model 6118-1. These were calibrated in the laboratory by adjusting the volume required to tip the bucket and by correcting the raingauge output readings. In the volumetric calibration, the effects of raingauge installation, the wetting of buckets, and the surface tension of the liquid used were considered. To calibrate the raingauge output, the recorded rainfall intensities were compared to the actual intensities calculated from the rate of inflow to the raingauge receiver. Recorded intensities were typically smaller than actual ones, in extreme cases by as much as 10%. This underestimate was explained by the loss of water during the bucket rotation. Estimates of these losses were made by timing the bucket movement for various rainfall intensities. The movement of the bucket from rest to the central position was found to take 0.3 – 0.6 seconds, depending on rainfall intensity. Finally, the sensitivity of the TBR output to the variations in the basic design parameters of the raingauge were studied numerically using the analytical expression derived for the recorded intensity.

Muller and Van Londen (1983) Compared the accuracy of three raingauges in use in the Netherlands. The Thies raingauge, the electrical Royal Netherlands Meteorological Institute (KNMI) rain gage, and the standard KNMI rain gage were compared with each other and with World Meteorological Organisation (WMO) requirements. The Thies drop counting system did not meet WMO requirements and was worse than the KNMI rain gages for the measurement of rainfall amounts. The Thies tipping bucket system results were so strongly dependent on the bucket cleanliness that errors of 5% were common. The use of such a system was not recommended. The electrical KNMI rain gage with float did not meet WMO requirements. The KNMI standard is simple, but an extra calibration is required if this gauge is used for comparative measurements

Met office (2000) The UK Met office carried out a trial to test the performance and long term reliability of some of the most common TBRs used in the UK. This was carried out at the Eskdalemuir observatory between January 1998 and June 2000. Gauges from Casella, Munro, Didcot instruments and Environmental Measurements were compared with the Met Office MK5 TBR and a standard five inch check gauge; 90 –95% of daily values produced by the gauges tested were within 10% of the check gauge reading. The Munro and Didcot gauges had the least scatter, with 80% of daily readings within 5% of the check gauge value. A possible seasonal variation in the results from the Casella gauge when compared to the check gauge was identified. It was suggested that this

might have been due to the plastic used for the buckets having a different co-efficient of expansion than that used in the other gauges.

3.7 Comparison with other Automatic Systems

Kreuels and Breuer (1986) Evaluated both a TBR and a drop size disdrometer (device for the optical detection and measurement of precipitation particles) on days with different wind speed and gust conditions. Both instruments were operated with a 1-min time resolution; and were carefully calibrated and system corrected. It was assumed that differing results would be due to environmental parameters. In the measurements of heavy storms with 1-min intensities as great as 90 mm/hr, deficits in water amount for the rain gage were found to be between 0 and 35%. Besides the wind, all other meteorological parameters were identical for both instruments. The drop size disdrometer was less susceptible to wind in regard to its installation. The only explanation for the water deficits was considered to be the influence of wind. To characterize this influence, it was suggested that the velocity of wind gusts rather than the mean velocity should be considered. It was suggested that new criteria should be developed to address the problems identified.]]

Hewston and Sweet (1989) Describe the use of a Weighing Tipping Bucket Raingauge (WTBR) developed by the Operational Instrumentation Branch of the UK Meteorological Office. In this device, the tipping bucket mechanism is suspended by a strain wire between the poles of a magnet. This wire is excited electrically at its resonate frequency, which is dependent on the tension in the wire due to the mass of the tipping bucket mechanism. As rain water from the collector enters the bucket, the tension on the wire increases, and there is a proportional increase in the resonate frequency of the wire. By measuring this change the rate of rain water accumulation can be calculated. The sharp change in resonant frequency as the bucket tips is taken into account in these calculations. The instrument was compared with a standard tilting siphon gauge on performance requirements for weapons systems trials, where accurate measurement of rainfall rate is required at all intensities and at sampling periods as short as 10 seconds. The WTBR proved to be close to the tilting siphon instrument in long term accuracy, but was far superior in resolving rainfall intensity down to 10 second increments, allowing accurate determination of rainfall intensity peaks.

Schonhuber, H.E. et. al. (1995) Compared data collected by a 2D video disdrometer and a standard TBR during winter storms in Austria. In an event of 20mm rainfall, in which intensity was up to 10mm h⁻¹ the disdrometer recorded 7% less than the TBR. However, the disdrometer was able to resolve light drizzle several hours before the TBR collected the first bucket of water.

Nystuen et al. (1996) Rainfall data from six different types of automatic rain gauge systems were collected for a set of summer rain events and for a set of winter rain events at Miami, Florida. The rain gauge systems included three types of collection gauges: weighing, capacitance, and tipping bucket; two gauges that inherently measure rainfall rate: optical scintillation and underwater acoustical inversion; and one gauge that detects individual raindrops: the disdrometer. All of these measurement techniques produced rainfall estimates that were highly correlated to one another. However, each method had limitations. The collection gauges were affected by flow irregularities between the catchment basin and the measurement chambers. This affects the accuracy

of rainfall-rate measurements from these instruments, especially at low rainfall rates. In the case of the capacitance gauge, errors in 1-min rainfall rates could exceed 10mm/h. The rainfall rate gauges showed more scatter than the collection gauges for rainfall rates over 5mm/h, and the scatter was relatively independent of rainfall rate. Changes in drop size distribution within an event could not be used to explain the scatter observed in the optical rain gauge data. The acoustical inversion method can be used to measure the drop size distribution, allowing rainfall classification and estimation of other rain parameters--for example, reflectivity or liquid water content--in addition to rainfall rate. The acoustical inversion method had the advantage of an extremely large catchment area, resulting in very high time resolution. The disdrometer showed a large scatter relative to the other rain gauge systems for low rainfall rates. This was consistent with the small catchment area for the disdrometer system.

Grossklau et al. (1997) described a new optical disdrometer optimized for use in high wind speed. The minimal detectable size of droplets is 0.35 mm. Each drop is measured separately with regard to its size and residence time within the sensitive volume. From the available information, the drop size distribution can be calculated with a resolution of 0.05mm in diameter either by evaluation of the residence time of drops or by drop counting knowing the local wind. Rain rates can be determined from the droplet spectra by assuming terminal fall velocity of the drops according to their size. Long-term simultaneous measurements of the disdrometer and a conventional rain gauge have been used to validate this procedure.

Nystuen (1999) Evaluated six different types of automatic rain gauges, including tipping bucket, weighing, capacitance, optical, disdrometer, and acoustical sensors.

These were deployed for 17 months (September 1993-January 1995) at the Atlantic Oceanographic and Meteorological Laboratory in Miami, Florida. Different rainfall conditions encountered during the experiment ranged from winter frontal rainfall to a tropical storm (Tropical Storm Gordon). Overall, all of the rain gauges performed well, with inter-correlation's of the order 0.9 or better using 1-min rainfall rates and biases of less than 10%; however, each showed limitations under different rainfall situations. In particular, under extremely heavy rainfall rates (over 100 mm/h), the disdrometer and tipping bucket rain gauges biased low, while the optical rain gauge biased high. Under light rainfall rates (under 2 mm/h), the capacitance and tipping bucket rain gauges showed significant instrument noise using a 1-min sampling interval. The optical gauge was sensitive to the relative proportion of small to large raindrops within the rain. The raindrop distribution parameter N_0 , the coefficient of the exponential fit to the drop size distribution, could be used to predict the optical gauge bias. When N_0 is large (relatively more small drops), the optical gauge biases high, and when N_0 is small (relatively more large drops), the optical gauge biases low. The acoustic rain measurement showed significant variability when compared to the other gauges. The acoustic measurement is very sensitive to the presence of very large raindrops (over 3.5mm diameter) as these raindrops are extraordinarily loud underwater and prevent the smaller drop size populations from being heard and accurately counted when they are present. While the range of wind speeds encountered during the experiment was limited, wind did affect the performance of several of the gauges. At higher wind speeds (over 5ms^{-1}), the disdrometer and acoustic rain gauges biased low and the instrument noise of the capacitance gauge increased significantly.

3.8 Discussion

There is general agreement among the authors of the papers reviewed that one of the most important factors affecting raingauge performance is exposure to wind. This effect increases with height above the ground surface, such that a gauge installed at 305mm above the ground surface may have a reduced catch of between 3% (lowland site) and 20% (upland site) compared to a gauge installed at ground level (BS 7843 1996). This factor may give rise to differences in catch between TBRs and check gauges when there is a relative difference in height between them. The British Standard, Met Office and WMO all suggest recommended methods of siting gauges to reduce exposure. These involve reducing or modifying wind flow over the collector by either locating at ground level ("pit gauge"), or constructing an earth (turf) bank to smooth wind flow. The relationship between exposure error (reduction in rainfall catch) and observed conditions is complex, although several researchers have developed models to describe the process (Robinson and Rodda 1969, Folland 1988). Recommended solutions for data correction are also given by the WMO. Design factors may reduce the effect of exposure, with evidence from several researchers (Folland 1988, Hughes *et al.* 1993) that "aerodynamic" gauges are measurably better than standard shapes. Commercially available raingauges have been produced (e.g. Environmental Measurements Ltd) using these designs.

A number of factors specific to the TBR have been identified. These include errors in recording caused by evaporation from the bucket, time of tipping and "bouncing" of the bucket. All of these parameters are likely to produce only small errors, and many can be reduced in a well-designed gauge. The most important effect identified in many of the reports reviewed relates to the relationship between TBR calibration error and rainfall rate. This is most marked during heavy rainfall, when water flowing in to the buckets while they are tipping can represent an error of up to 10 – 30% compared to a co-located storage gauge (BS 7843 1996 and others). The nature of this rainfall/rate error relationship has been described as non-linear (Calder and Kidd 1978, Humphrey *et al.* 1997), but in the British Standard is described as linear between 0 and 100mm/hour. The solution to this problem favoured by some national meteorological services (UK Met Office, Canadian Atmospheric Environment Service), has been to apply a correction factor derived from the ratio of mean daily TBR readings compared to check gauge readings. This approach relies on the availability of a daily read check gauge, and would not be suitable for correcting event based sampling where accuracy within small time steps is required. The alternative, outlined by a number of researchers (e.g. - Calder and Kidd 1978, Niemczynowicz 1986, Humphrey *et al.* 1997), is to carry out a dynamic calibration of the TBR in order to quantify the error over a range of rainfall intensities. A number of the papers reviewed suggested numerical methods describing this relationship.

Alternative automatic systems reviewed include developments of the TBR such as the weighing TBR (Hewston and Sweet 1989). This instrument has the potential to achieve a much higher resolution than the standard TBR, although retains the possible inaccuracies associated with the tipping mechanism. Cost may preclude its use in extensive networks, as commercial models are three times as expensive as standard TBRs (C Addis 2001, personal communication). Optical/video measurement of precipitation using a disdrometer to measure and evaluate individual particles has been developed in the last 20 years, often in conjunction with weather radar systems (to

provide “ground truth” information). Several researchers have shown good correlation between these systems and direct measuring raingauges including TBRs (e.g. Schonhuber, H.E. *et al.* 1995 Nystuen 1999). Disdrometers have the added advantage of detecting and differentiating the nature of precipitation (rain, snow, hail etc) as well as its quantity, and can operate in all wind conditions. At present disdrometers are used as tools for investigating the nature of precipitation, and are usually close to the necessary data processing facilities.

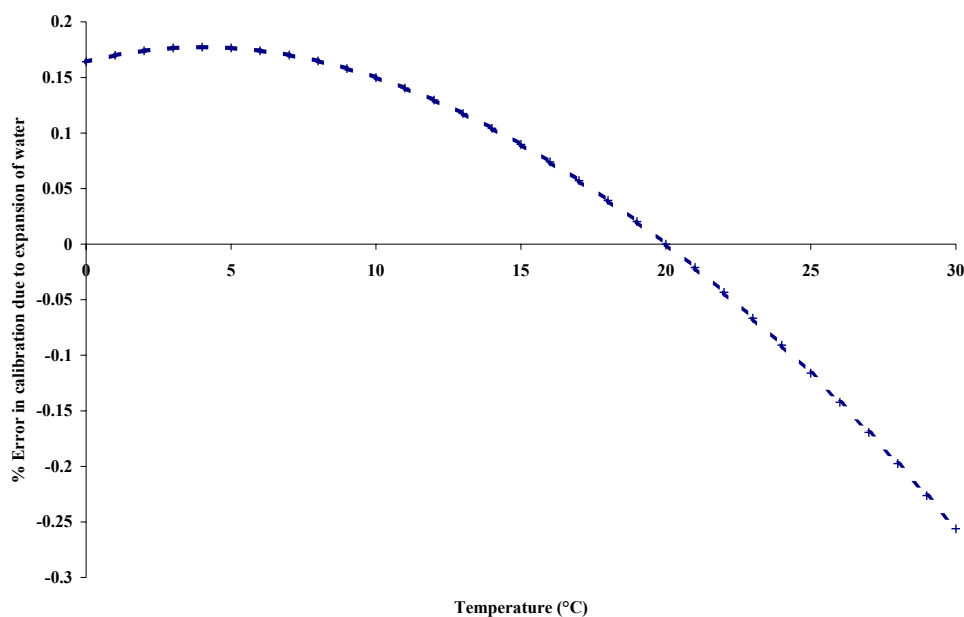
4 LABORATORY STUDIES

4.1 Introduction

The Environment Agency routinely collects hydrometric data for flood risk prediction, flood warning and water resource planning activities. As part of this work they have identified discrepancies between the records obtained from tipping bucket raingauges (TBRs) and conventional storage gauges. The problem that has been identified, namely under-recording by TBRs, has particular implications for work relating to water resources since, whilst the error may be relatively small on any one event, the significance may increase as rainfall totals are accumulated over longer periods. The Agency standard gauge has a calibration coefficient of 0.2 mm per tips as standard (i.e. 1 tip = 0.2 mm). This bucket 'calibration coefficient' of 0.2 mm is used for each tip over the whole range of rainfall intensities measured; i.e. they do not apply a dynamic calibration coefficient. When dynamic calibration is used a range of calibration coefficients are determined and applied to better reflect the volume of water per tip at different intensities.

Work was needed to determine whether the discrepancy between the two systems was systematic and could be linked to specific factors, or occurs randomly. If the error was systematic, and was linked to some specific variable, such as a deficiency of the calibration method, data correction may be possible. The factor that was thought to most likely to be critical to calibration was rainfall intensity, although temperature may also play a part. It has been reported in the literature (Calder and Kidd, 1978) that dynamic calibration of TBRs was required to achieve both high resolution and accuracy. They stated that in general, a non-linear relationship existed between flow rate and the tipping rate of a tipping-bucket gauge. This difference arose from the fact that it took a finite but fixed time for the bucket to tip. As a consequence of this, an amount of rainfall could fall into an already full bucket during the time taken to tip. This amount increased with the rainfall intensity and as a consequence rainfall is underestimated. The use of a calibration curve covering a range of intensities has been recommended by a number of workers, for example, Niemczynowicz (1986). Other methods have also been proposed to either avoid or correct for this non-linearity, including the use of a siphon that is incorporated between the receiver and the bucket and is designed to empty at a constant flow rate into the bucket. However, such solutions, while providing a better measurement of total rainfall, smooth out the measurement of peak intensity.

Raingauges supplied by different manufacturers may perform differently and performance may also change with time depending, for example, on the robustness of the equipment and the environmental conditions under which it is used. Depending upon the type of material used to construct the gauge, expansion and contraction due to changes in operating temperatures may also influence the accuracy of measurement. In this context, it may be useful to consider the effect of changes in temperature on the method used for calibration. The main effect, however, will be derived from the change in density of water with temperature. As the density of water decreases, a greater volume will be required to achieve the critical mass necessary for the bucket to tip. The impact of change in temperature on rainfall measurement is shown in Figure 4.1 for a gauge calibrated at 20°C.



(Plot derived from information on changes in water density with temperature reported in Weast, 1971)

Figure 4.1: Percentage error in rainfall measurement as a consequence of the difference between calibration temperature (20°C) and operational temperature due to changes in density of water.

4.2 Detailed Methodology

This was undertaken using 24 new rain gauges of 8 different types which are identified by numbers 1 to 8 to ensure confidentiality.

General Gauge Characteristics

- type 1 – conventional metal TBR manufactured in UK
- type 2 – conventional metal TBR manufactured in UK
- type 3 – conventional metal TBR imported from outside Europe
- type 4 – stainless steel aerodynamic TBR manufactured in UK
- type 5 – conventional metal and plastic TBR made within Europe
- type 6 – all stainless steel conventional metal TBR imported from outside Europe
- type 7 – plastic aerodynamic TBR manufactured in UK
- type 8 – conventional metal TBR manufactured in UK

4.2.1 Evaluation of calibration methods

Each rain gauge was unpacked, assembled according to instructions (where provided), mounted on a level base in a 20°C constant temperature room and then the calibration checked using the two different methodologies.

Burette Method

The buckets on each gauge were labelled A and B and the volume required to make both the A and B bucket tip was measured by dripping in water from a 20 ml burette following the standard procedure (BS 7843 2.1, 1996).

Constant Rate Method

A special rig was set up whereby eight gauges could be calibrated simultaneously. The rig used a Watson Marlow 505U peristaltic pump fitted with two 4-channel pump heads attached to the drive shaft. This pump/head configuration is the standard equipment used by the Environment Agency for calibration of raingauges using the constant rate method. The target range for the rainfall intensity at which the gauges were calibrated was between 10 and 12 mm hr⁻¹. Since the volume required to tip the bucket for each gauge is a function of funnel diameter, a different flow rate was required for each gauge to meet the intensity required for calibration. As only a limited number of pipe sizes were available for the peristaltic pump, each type of gauge was calibrated at a slightly different rate. The pipe sizes used were selected such that for the chosen speed of rotation (48 rpm) all gauges received water at a rate that fell within, or very close to, the target range. The rotation speed was chosen as, combined with the available pipe diameters, it allowed calibration of all eight gauges simultaneously at an intensity within or very close to the target rate. Each calibration test was run for two hours.

The gauges were set up on a specially designed bench such that the delivery from each bucket could be collected in a beaker. All the gauges were connected to a NEWLOG datalogger set to record the number of tips in each 5 minute time interval.

The specific procedure used was as follows:

Prior to testing, each gauge was wetted by running 0.5l of water through it. Each intake pipe from the pump was placed in an individual reservoir and the pump was then run until all air had been expelled from the system. The pump was then stopped and the reservoir refilled and weighed. A clean labelled and pre-weighed beaker was then placed under the collection point below each bucket. The datalogger was then started and the pump set to run for two hours using a digital time switch. At the end of the test the reservoir and collection beakers were reweighed. Gauges were adjusted and calibration checked repeatedly until they met the criteria that the calibration coefficient was within 2% of 0.2mm, and the amounts of water required to tip each bucket were within 5% of each other. A further two runs were then made, without adjustment and the mean of these three runs was taken to be the calibration coefficient for the gauge concerned. This procedure produced, on occasions, mean calibration coefficients that fell slightly outside the acceptable range of +/- 2% error of rainfall measurement. The individual calibration coefficients determined for each gauge will be applied to the data from each gauge when deployed in the field study.

4.2.2 Effect of temperature at time of calibration on calibration coefficient obtained using the constant rate method.

Experimental design

The 24 rain gauges were divided into three gauge sets (blocks) each containing one example of each type of gauge. The first and third sets of gauges were set up in the constant temperature at laboratory at 20°C and calibrated using the constant rate method (as detailed above). As previously stated, once a gauge had come into calibration, two

further measurements were made to provide three values that could be used to produce a mean calibration coefficient for the gauge.

Statistical analysis of data

The statistical analysis was undertaken in accord with the experiment design, which can be regarded as a criss-cross design, in which rows of the data can represent temperature, and columns can represent gauges. The triplicate readings were nested in the column-row structure and are not replicates of gauges but replicate estimations of the response of a single gauge in each block. Thus the temperature, gauge, and gauge interaction had 1,7 degrees of freedom (when 8 gauges were used) and 7 degrees of freedom respectively. The gauges, temperature and interaction have their separate residual errors and associated p-values and the within-gauge variation was represented by the mean square error of the blocks/row/column/rep stratum. Of particular importance in data interpretation, was the gauge/temperature interaction. If there was a statistically significant interaction then this should be scrutinized and any temperature effect questioned. Since each gauge had been set to a unique, though similar coefficient, a significant gauge effect has no relevance. This approach could only be applied to the combined data from sets one and three where the direction of temperature changes had been the same. An analysis using the data from all 3 blocks was undertaken where the block 2 data were extracted for the sequence 20° to 4° degrees Celsius and merged with similar data from block 1 and 3 data; this just compared the difference between the two temperatures. Analysis of variance was undertaken using GENSTAT (Alvey et al, 1972) and regression analysis using STATISTICA.

4.2.3 Effect of rainfall intensity on gauge calibration coefficient

The relationship between calibration coefficient and the simulated rainfall intensity at which it was measured were determined for each gauge type. The rainfall intensities at which calibrations were undertaken encompassed the range 1- 100 mm hr⁻¹ with target intensities of 100 mm hr⁻¹, 50 mm hr⁻¹, 40 mm hr⁻¹, 30 mm hr⁻¹, 20 mm hr⁻¹, 10 mm hr⁻¹, 5 mm hr⁻¹ and 1mm hr⁻¹. In each case, the pump settings used and the actual rainfall rate achieved were recorded. All dynamic calibrations were undertaken in an environment where the temperature was maintained at a constant 20°C. Measurements at each rainfall intensity were replicated three times for each gauge and three gauges from each manufacturer were calibrated. The numbers of tips were recorded, as was the outflow from each bucket. Tests were either carried out using the Watson Marlow eight channel pump or, at intensities that required a flow rate in excess of 30 ml minute⁻¹, using an Altec single channel peristaltic pump. The test procedure used was identical to that described in section 5.2.1.

4.2.4 Long-term reliability tests

Two replicates of each gauge were subjected to a simulation which generated the equivalent number of tips to that which would be obtained from 10 years use in a climate with 1500 mm per annum rainfall. A special rig was used for the long-term tests, which utilized a range of peristaltic pumps manufactured by Autoclude. This allowed water to be input to each gauge at a constant and pre-defined rate. The rate selected was as close to 75 mm hr⁻¹ of rainfall as could be obtained given the limitation imposed by the available pump speeds and tube diameters. The rate of 75 mm hr⁻¹ was chosen to minimize the time take for a single years run. This enabled the completion of the test within the timescale required so that the gauges could be deployed for field testing by January 2002.

Prior to starting the tests each pump/tube combination was run in for minimum of 12 hours. The pumps were controlled by a time switch that stopped the pump after periods equivalent to 1 year, 2 years and 10 years rainfall so that spot checks on the calibration of the gauge could be carried out. The number of times each tipping bucket tipped was recorded on a Newlog datalogger running at a 5 minute time interval. A record was kept of any breakages that occurred or faults that developed. If any gauge failed to operate, for a reason that required repair to the gauge itself, rather than from external influences, then it was deemed to have failed testing and testing of that gauge ceased.

4.2.5 Observations on gauge performance and ease of use

A record was kept of specific problems and difficulties encountered when calibrating the gauges;

4.3 Results

4.3.1 Evaluation of calibration methods

A comparison of the results of applying the two calibration methods to the gauges under test is shown in Figure 4.2. The comparison uses the measured calibration coefficient s to calculate the amount of rainfall needed to achieve 7500 tips, which if the calibration coefficient is 0.2 should be 1500mm. This data shows that not only do the two calibration methods clearly give a different result, but also the considerable variability in actual calibration of new gauges as received from the manufacturer. Data for gauge type 8 are not presented due to an error in assembly which compromised the results of this test for this gauge.

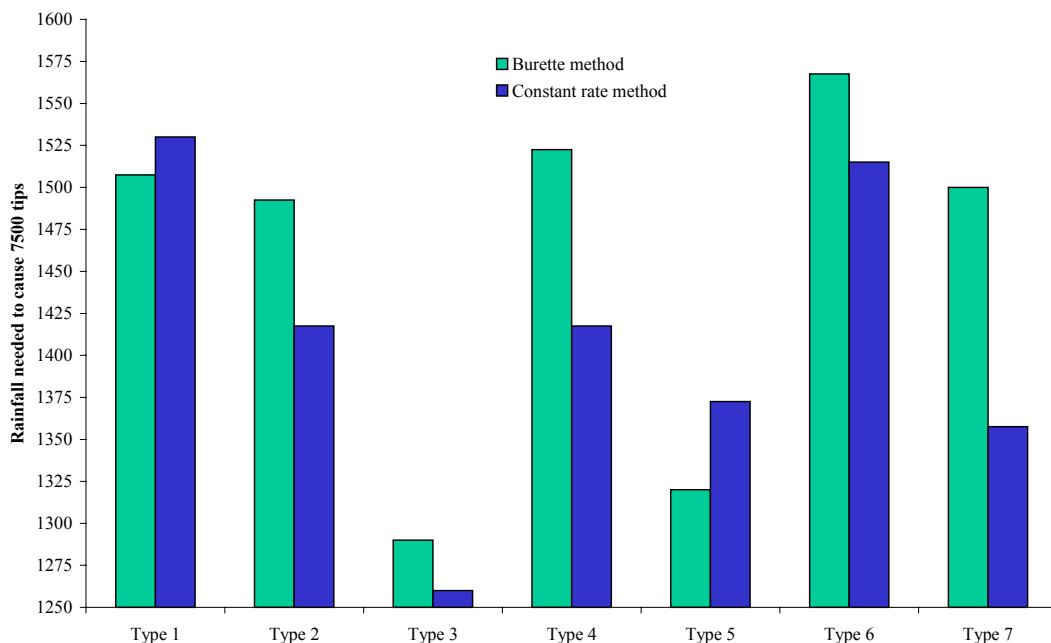


Figure 4.2: Relationship of rainfall required for 7500tips and calibration method

4.3.2 Effect of temperature at time of calibration on calibration coefficient obtained from constant rate method

The effect of changing temperature (20°C to 4°C and 4°C to 20°C) and movement on measured calibration coefficients of the gauges are summarized in Table 4.1. Differences between the calibration coefficient measured at 20°C and that measured at 4°C are small in most cases.

Table 4.1: Summary of temperature testing based on all 3 blocks

	Gauge type							
	No 1	No 2	No 3	No 4	No 5	No 6	No.7	No. 8
Mean calibration coefficient at 20°C	0.191	0.189	0.197	0.196	0.201	0.226	0.201	0.208
Mean calibration coefficient at 4 °C	0.196	0.196	0.195	0.195	0.193	0.196	0.199	0.202
% Difference between 4°C and 20°C	2.91	3.84	0.91	0.17	4.14	15.23	0.95	2.85

If moving the gauges had no effect, then returning the gauges to their starting temperature should return the calibration coefficients to their original values; this was clearly not the case, but in most cases differences due to this factor were small. Despite the minimal impact of temperature on measured rainfall; the data presented have been corrected to take account of the changes in the density of water that occur between 20°C and 4°C. The changes represented here thus represent the impact of changing temperature on the instruments themselves, or of moving the instruments. Clearly gauge type 6, stands out as the being the most affected of the gauges. After the gauge type 6, the next most affected by temperature changes was type 5. It is interesting to note that the type 6 gauges were constructed entirely of stainless steel and the mechanism of type 5 was predominantly plastic.

Analysis of variance, using a criss cross design, of the combined data obtained from gauge sets 1 & 2 showed that the difference in calibration coefficients that occurred as a consequence of moving the gauges (initial compared to end) was not statistically significant ($P > 0.5$). However, the difference due to changes in temperature were ($P < 0.05$). When the data relating to the type 6 gauges were excluded from the analysis the difference caused by temperature changes was no longer statistically significant. Thus although there were clearly differences arising from both factors in the case of all of the gauges, the variation due to movement falls within the repeatability of measurement of the calibration coefficient (for the gauges).

Analysis of variance using all three sets of data, each as the blocks, and looking at the difference between first temperature and second temperature i.e. 20-4°C and 4-20°C showed that there was a significant gauge-temperature interaction ($P = 0.022$). When the data from the type 6 gauge were excluded from the analysis, the significance level remained similar ($P = 0.017$). Examination of the means suggest that this significant interaction arises from the divergent behaviour of the gauges e.g. type 1 calibration coefficient goes from 0.196 at 20°C to 0.191 at 4°C, whereas the type 5 goes from 0.193

at 20°C to 0.201 at 4°C. This divergence amplifies the gauge interaction causing the difference to be significant. The actual magnitudes of the changes for the gauges (+0.005 to -0.008), other than the type 6 are similar to the standard error of difference (0.004899) and this suggest that these differences are not truly significant. Thus only in the case of type 6 gauges was calibration significantly influenced by temperature changes.

4.3.3 Effect of rainfall intensity on gauge calibration coefficient

The % errors generated by applying a calibration coefficient determined at 10-12 mm hr⁻¹ over a range of simulated rainfall intensities are presented in Figure 4.3. The data from all the gauge types shows a similar trend, with some overestimation of total rainfall at low intensities and then underestimation as rainfall intensity goes above that at which the gauge was calibrated. Individual gauge specific relationship, between % error and rainfall intensity, can be calculated (Table 4.2) although the strength of these relationships varies considerably. A single generalized relationship was also calculated using the data from all the gauges and this is shown with the data in Figure 4.4

Table 4.2: Relationship between Rainfall intensity and % error compared to calibration at 10 mm hr⁻¹

Gauge type	Polynomial Regression	R ²
1	$Y = 0.164741 - 0.0891X + 0.000204X^2$	0.228
2	$Y = 0.338803 - 0.102475X + 0.000163X^2$	0.649
3	$Y = 0.937434 - 0.128398X + 0.000294X^2$	0.775
4	$Y = 0.522824 - 0.123834X + 0.000565 X^2$	0.397
5	$Y = 1.51539 - 0.100015X + 0.000055X^2$	0.687
6	$Y = 0.765467 - 0.159311X + 0.000687X^2$	0.628
7	$Y = 2.28896 - 0.339171X + 0.00229EX^2$	0.384
8	$Y = -0.24 - 0.0210X - 0.000667X^2$	0.615
All gauges	$Y = 0.523 - 0.107X + 0.000254X^2$	0.519

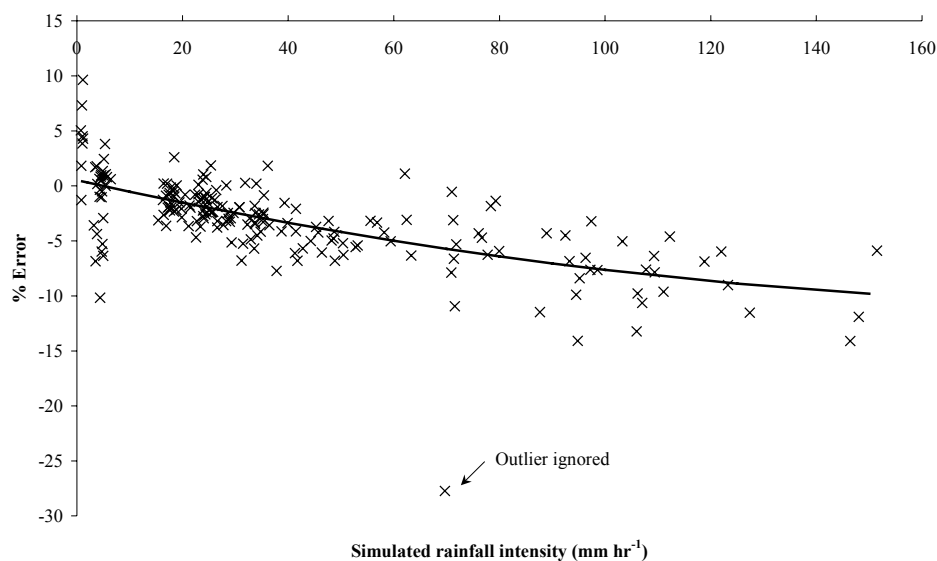


Figure 4.3: Overall Relationship between % error and rainfall intensity for gauges calibrated at 10-12 mm hr⁻¹.

4.3.4 Long-term reliability tests

The mean error in the measurement of rainfall as a consequence of drift in calibration coefficient over a period of 10 years simulated rainfall is shown in figure 5.3. No breakages or failure of any kind were recorded on any gauge during the test. It is important to note that in a number of cases most of the drift occurred within the first year.

On average the drift in the calibration did not result in an error of measurement of more than +/- 4.5%. Drift was not linear with time and with some gauges the impact on percentage error of measured rainfall was ca. 3% after only one-year and then subsequently decreased again from 2-10 years. In the worst individual case (replicate 2 of Gauge 6), the error in measurement increased by nearly 8% in the first year. Some gauges (type 5 & 7) were particularly resistant to drift. However, as only two gauges of each type were tested it would be inappropriate to recommend that these gauge types can be used in the field for longer than the others without calibration

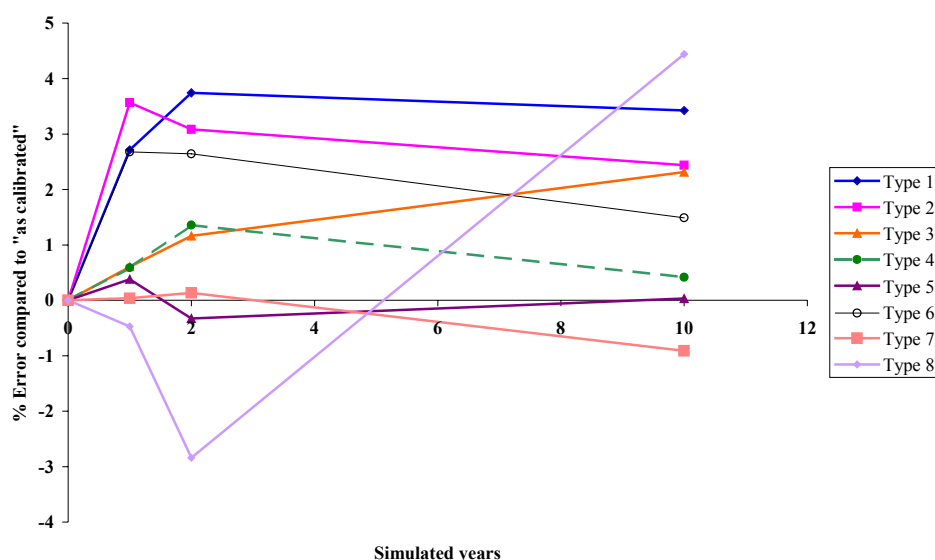


Figure 4.4: Change in % error in measurement due drift in calibration with time (based on simulated rainfall)

4.3.5 Observations on gauge performance and ease of use

All of the gauges, with the exception of types 5 and 7, could be placed directly on the calibration rig without any modification. Neither type 5 nor 7 were constructed in such a way whereby the water could be collected easily individually from each of the buckets, thus making verification of the balance difficult. In the case of the type 7 gauges this was relatively easily overcome by drilling additional holes in the base of the rain gauge. However, type 5 did not lend itself to this modification. The only way in which it was practicable to collect individually the water from each of the buckets was to dismantle the gauge and rotate the tipping bucket mechanism on its mounting pedestal so that it was no longer located immediately above the base plate. This is not regarded as particularly satisfactory solution as it resulted in the gauge being calibrated in a configuration other than that in which it was being used.

type 1

The small adjustment nuts were fiddly, making fine adjustment difficult.

type 2

This was provided with 5mm adjustment bolts which were easy to adjust, making it one of the first gauges to be brought into calibration. However, gauge number 2 was found to lock up in central position with water pouring either side of the bucket divider. When the gauges was examined by the supplier's engineer, following failure under test, it was found that the reed switch and magnet had been set too closely together during the manufacturing process.

type 3

Too many adjustment fasteners (three) but a very good bucket design, water empties completely, due to small wire on the bucket.

type 4

Very easy to adjust but very shallow bucket angle plus a rough texture of the surface leads to water retention after tip.

type 5

Easy to adjust, but no locking nuts. Some collection losses due to splashing and had to be modified to allow calibration.

type 6

This gauge was very difficult to adjust due to poor quality plastic screws that wore very rapidly. The bucket empties well but when filling, water almost runs over central divide before tipping, which could present problems if the bucket balance starts to drift during use.

type 7

This gauge appeared good to adjust at first but it was difficult to get the calibration exactly right. Responded erratically to adjustment this could be due to asymmetry in hemispherical stops. Good visual markers on stops aided adjustment. The bucket holds a lot of water after tipping which could be lost due to evaporation causing small error if subsequent tip is sometime later.

type 8

This was very easy to adjust, however, in the absence of an instruction manual; the bucket can be incorrectly inserted, even by technical staff used to setting up TBRs, causing it to be a long way out of calibration. One of the gauges supplied was found to have a defective reed switch. The replacement of this was found to be quite difficult.

4.4 Discussion

4.4.1 Effect of temperature at time of calibration on gauge calibration coefficient and its impact on rainfall measurement

The type 6 gauges (all stainless steel construction) were particularly susceptible to temperature changes and the calibration coefficients of these gauges also changed considerably due to movement. The impact of the change in calibration coefficient due to temperature would have the effect of causing over 8% error in rainfall measurement from a gauge calibrated at 20°C but deployed at lower temperatures (4°C). The exact cause of this change is uncertain but it must assumed to be due to expansion changing the amount of force required to tip the buckets. It may be that the all stainless steel design makes this gauge more susceptible to changes. The changes in the other gauges due to temperature were of a much smaller magnitude and had a much smaller impact on the error of measurement. However, even changes as small 1% which are observed with most gauges, could be sufficient to effectively take a gauge out of the allowed calibration tolerance. The error due changes in calibration coefficient due to temperature will be added to that inherent in the use of a standard 0.2mm per tip coefficient to convert tips to rainfall. Thus if the actual calibration coefficient of a gauge is for example deviates from 0.2 by -1.8% at 20°C and there is a further drift of -1% due to temperature change from 20° to 4°C then the total error will be -2.8% at 4°C. Thus if gauge specific calibration coefficients were used to convert tips to mm of rainfall rather than a standard 0.2mm, the total error will be reduced since the inherent error due to difference between actual and assumed calibrations will be removed. An alternative approach would be to ensure that the inherent error was always in the opposite direction to any temperature generated errors, i.e. if temperature error for specific gauges is

negative calibrate gauges to between 0 and +2% rather than +/- 2%. In this way the errors would cancel each other out.

The impact on error of measurement was inverse when the gauges were calibrated at 4°C and used at 20°C. Thus an alternative approach to error reduction might be to calibrate at the most common temperature at which rainfall occurs when deployed in the field. However, as this temperature would vary spatially and temporally this approach might prove to be complex to implement. Consideration of the range of temperatures encountered in the UK suggests that 20°C should certainly be the maximum temperature at which gauges are calibrated if errors are to be minimized.

4.4.2 Effect of rainfall intensity on gauge calibration coefficient

All of the gauges tended to increasingly underestimate rainfall at higher intensities, which is in line with the findings of other workers. Niemczynowicz (1986) tested three different types of gauges and found, for example, under reading of 10% at 300 mm hr⁻¹ with the PLUMATIC raingauge. Similarly, Marsalek (1981) carried out laboratory calibrations on three TBRs available in Canada and found that recorded intensities were typically smaller than actual ones, in extreme cases by as much as 10%. The mechanism by which this under recording occurs is that due to the finite time it takes for a bucket to tip some water will fall into a full, but already moving, bucket (Calder and Kidd, 1978). Relationships between intensity and percentage error, for both individual gauges and the overall data set, were non-linear. This is in accordance with the findings of Calder and Kidd (1978) who stated that in general, a non-linear relation exists between flow rate and the tipping rate of a tipping-bucket gauge. Further support for the non-linearity of the relationship comes from the work of Humphrey *et al* (1997) who tested 5 types of commercial TBRs and found that all exhibited large non-linear underestimation errors (between 5% and 29%) that decreased with increasing rain gauge resolution and increased with increasing rainfall rate, especially for rates greater than 50mm h⁻¹.

The impact of this intensity dependence of calibration on rainfall records will vary according to the frequency with which higher rainfall intensities occur at the location where a specific gauge is being used. The variability in the data suggests that a large number of determinations will be required to develop a robust relationship between intensity and percentage error for a specific type of gauge. However, given the relatively small number of different gauge types used by the Environment Agency this should not prove an insurmountable problem. Should a decision be made to adopt error correction, to offset the affect of the intensity dependence of the calibration, then it is recommended to undertake a pilot study on a single gauge type. A carefully determined correction factor could then be used to correct the data to take account of intensity effects. This test should be possible on one of the datasets where the agency have identified a discrepancy between the check gauge and tipping bucket totals.

An alternative solution to the problem could be to use TBRs with buckets with a larger volume per tip, for example 0.5 mm. This would decrease the tipping rate and hence reduce the error. However, adopting this solution would tend to increase evaporation losses during summer due to the increased residence time in the bucket following small amounts of precipitation.

4.4.3 Long-term reliability tests

The fact that the long-term reliability tests produced no failures suggests that it is corrosion in the outdoor environment that is the key cause of failure rather than just repeated tipping. However, the tests have provided useful data supporting the need for regular calibration of tipping bucket raingauges if first class accuracy is to be maintained. Based on the rate of drift, an annual calibration should be adequate in areas where rainfall is less than 750 mm per annum. In areas where there is higher rainfall, or if a high degree of precision were required, then biannual calibration would provide a better control as in many cases most drift occurred during the first year's simulation.

4.4.4 Observations on gauge performance and ease of use

Unless a special calibration rig can be obtained from the manufacturer the use of the type 5 gauge is not recommended due to the need to calibrate in a different configuration to that in which it is used. The gauge would also be substantially improved by fitting with more robust adjusting screws. In general manufacturers need to look to design gauges to make adjustment easy, thus an easy to use gauge is one that has the largest adjusters. Other things to be avoided are any asymmetry in the shape of the stops, which control the bucket volumes as this causes erratic calibration.

The gauges where the bucket surface was rough tended to retain more water after the bucket had tipped than those where it was smooth. The effects of this will be to slightly increase the volume required at the next depth if sufficient time passes to allow this small volume of water to evaporate. However, the amounts of water concerned are so small that the impact of this "increased wetting up error" on the rainfall record will be minimal.

4.5 Overview of a Calibration Methods

The continuous rate method has a significant advantage in that it provides an approach which is closest to the mode of operation of the gauge during rainfall and the calibration coefficient at least takes account of losses that occur during tip time at the intensity at which it is calibrated. As a consequence, underestimation of rainfall due to losses during time it takes the bucket to tip are likely to be greater with gauges which are calibrated by the burette method. However, it could be argued that the burette methods would provide a better calibration for very fine low intensity rain than calibration at ca. 10-mm hr^{-1} .

The standard Environment Agency constant rate method is based on filling a calibration rig with a known volume of water from a volumetric flask and then running the pump, which supplies water to the gauges, until it is empty as described in the Environment Agency, Hydrometric Manual. However, using this method, it is difficult to be sure of the exact amount of water that has been put into the gauge since the residues retained in the system may be variable. The method used by ADAS in this study (section 3.2) overcomes this problem by making a direct measurement of the water input which can be compared against the amount collected from the buckets with confidence.

Neither the burette method nor the constant rate method themselves would be expected to be particularly affected by temperature changes. In the case of the constant rate method this is because a direct measurement of the mass of water delivered to the gauge is made. Any changes in pump delivery rate that might occur due to temperature

changes are irrelevant unless the errors become gross and this is unlikely. In the case of the burette method the burettes themselves are normally calibrated for use at 25 degrees C. Decreasing temperature will tend to reduce slightly the volume delivered. However, to some extent this will be balanced by the change in the water density. In any case it is a quite simple matter to calibrate the mass of water delivered by the burette against temperature.

The greatest scope for error in the constant rate method is splashing losses between the buckets and the collection vessels. However, controls can be put in place such that this is detected and kept within acceptable limits. If larger diameter gauges are tested, such as the FSS500, it is suggested that a larger volume of water be used for the test to increase the number of tips counted. However, this will also increase the time taken for the test, which may have logistical implications. If the same volume of water is used with a large diameter gauge as a small one, then the number of tips counted is significantly reduced. The greater the number of tips counted, the more precise the estimate of the calibration coefficient is likely to be. If it were feasible to set the gauges up to run unattended on the calibration rig, then an increase in the volume of water used would be desirable for all gauges, as this would increase the number of tips counted.

4.6 Specific Conclusions arising from Laboratory Tests

The constant rate method of calibration should provide a calibration coefficient that is more robust at higher intensities than one measured by the burette method.

Gauges calibrated by the constant rate method will underestimate at higher rainfall intensities and better precision could be obtained by use of a full dynamic calibration

The calibration coefficient of tipping bucket rain gauges varies with temperature although in most gauges the change is small

The influence of temperature on the calibration methods is likely to be small and can be corrected for.

Tipping bucket rain gauges need at least annual calibration and possibly biannual in high rainfall areas.

5 FIELD TESTING OF GAUGES

5.1 Introduction

The Environment Agency routinely collects hydrometric data for flood risk prediction, flood warning and water resource planning activities. As part of this work discrepancies have been identified between the records obtained from tipping bucket raingauges (TBRs) and conventional storage gauges. The problem that has been identified, namely under-recording by TBRs, has particular implications for work relating to water resources since, whilst the error may be relatively small on any one event, the significance increases as rainfall totals are accumulated over longer periods. The Agency standard gauge has a calibration coefficient of 0.2 mm per tips as standard (i.e. 1 tip = 0.2 mm) which is measured at a rainfall rate of ca. 10 mm hr⁻¹. This measured bucket 'calibration coefficient' of 0.2 mm is used for each tip over the whole range of rainfall intensities measured; i.e. they do not apply a dynamic calibration coefficient. When dynamic calibration is used a range of calibration coefficients are determined and applied to better reflect the volume of water per tip at different intensities.

Work was needed to determine whether the discrepancy between the two systems was systematic and could be linked to specific factors, or occurred randomly. If the error was systematic, and was linked to some specific variable, such as e.g. a deficiency of the calibration method or rainfall intensity, data correction may be possible.

The factor that was thought to most likely to be critical to calibration was rainfall intensity, although temperature may also play a part. It has been reported in the literature (Calder and Kidd, 1978) that dynamic calibration of TBRs was required to achieve both high resolution and accuracy. They stated that in general, a non-linear relationship existed between flow rate and the tipping rate of a tipping-bucket gauge. This difference arose from the fact that it took a finite but fixed time for the bucket to tip. As a consequence of this, an amount of rainfall could fall into an already full bucket during the time taken to tip. This amount increased with the rainfall intensity and as a consequence rainfall is underestimated. The use of a calibration curve covering a range of intensities has been recommended by a number of workers, for example, Niemczynowicz (1986). Other methods have also been proposed to either avoid or correct for this non-linearity, including the use of a siphon that is incorporated between the receiver and the bucket and is designed to empty at a constant flow rate into the bucket. However, such solutions, while providing a better measurement of total rainfall, smooth out the measurement of peak intensity.

The other main factor thought to be likely to influence catch was over-exposure (to wind). This is identified as the most important factor contributing to loss of catch by all rain gauges (BS 7843 2.1, 1996). Similarly, the World Meteorological Organisation (1994) states that the suggested aim when selecting a site for a gauge would be to choose a location that gives the minimum possible wind speed over the gauge orifice, without blocking precipitation by surrounding terrain. The impact of exposure to wind on rain gauge catch has been well documented in the literature e.g. Folland (1988) who suggested a new design of raingauge ("flat champagne glass gauge") which aimed to substantially lower the systematic losses of rainfall volume in the high winds commonly found over exposed areas of land. Tests of a prototype "champagne glass" and a

production model “cone” gauge found that these “aerodynamic” models had the capacity to improve rainfall catch, and could be exposed well above ground in windy conditions while still giving reasonable results (Hughes, Strangeways and Roberts, 1993). Therefore, as “champagne glass” tipping bucket rain gauges are commercially available and the Environment Agency have purchased a number model for use in high exposure situations there was also a need to understand what impact the use of this type of gauge may have on the rainfall record. In addition the Agency own a number of other makes of gauge and needed to identify the key characteristics that make a TBR function well

Therefore a field trial was established to compare, in the field, the performance of eight different patterns of TBR against that of a standard meteorological office 5" gauge.

5.2 Materials and Methods

5.2.1 Experimental site

The experimental site was located at Eskdalemuir Observatory in Dumfries and Galloway, which is situated in the Southern Uplands of Scotland (figure 5.1). The Observatory, which is 3½ miles NNW of Eskdalemuir Church, occupies a site of about 11 acres on a rising shoulder of moorland, bounded, on the East, by the Ettrick and Selkirk road, on the West by a small stream (Davington Burn) and on the South by the village of Davington.

The hillside in the vicinity of the Observatory slopes generally from NW to SE, the mean height above sea level being 800ft or 244 metres. Cassock Hill, slightly more than a mile distant to the NW, is (367m) while the benchmark at Davington School, ¼ mile to SE is 699ft (213m) above MSL. To the East, the ground slopes fairly rapidly to the valley bottom. The height at the River White Esk, at a point due East of the Observatory and about mile away being 675ft(208m) above MSL. Beyond the river, Dumfedling Hill rises to a height of nearly 1200ft (366m) above MSL. Some 4-5 miles away to the North is a high ridge, the highest point of which is Ettrick Pen (to NNW) 2270FT(700M) above MSL. Rather more than half a mile to the West, the ground rises to 1040ft (317m) and reaches nearly 1200ft(366m) a further half mile on. To S and SSE, The Observatory commands a view of the White Esk Valley as far as Hartmanor, 4 miles away. Beyond, the upper slope of Cauldkine Hill, about 10 miles distant, is visible.

The National Grid Reference of the site is NT 32356026 and the station is located at an altitude of 242 m. Long-term average annual rainfall for the site is 1567mm.

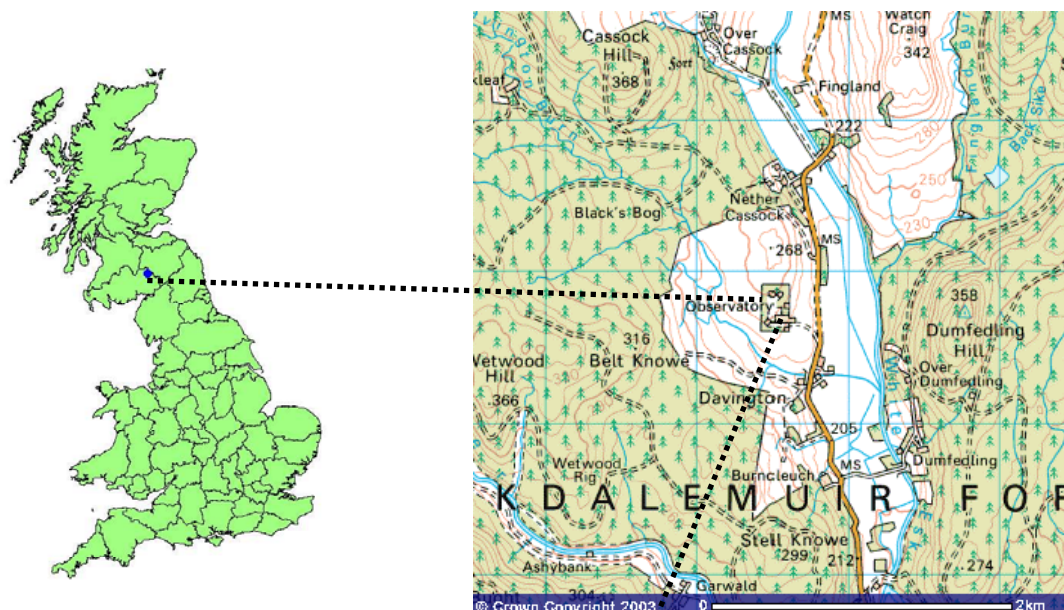


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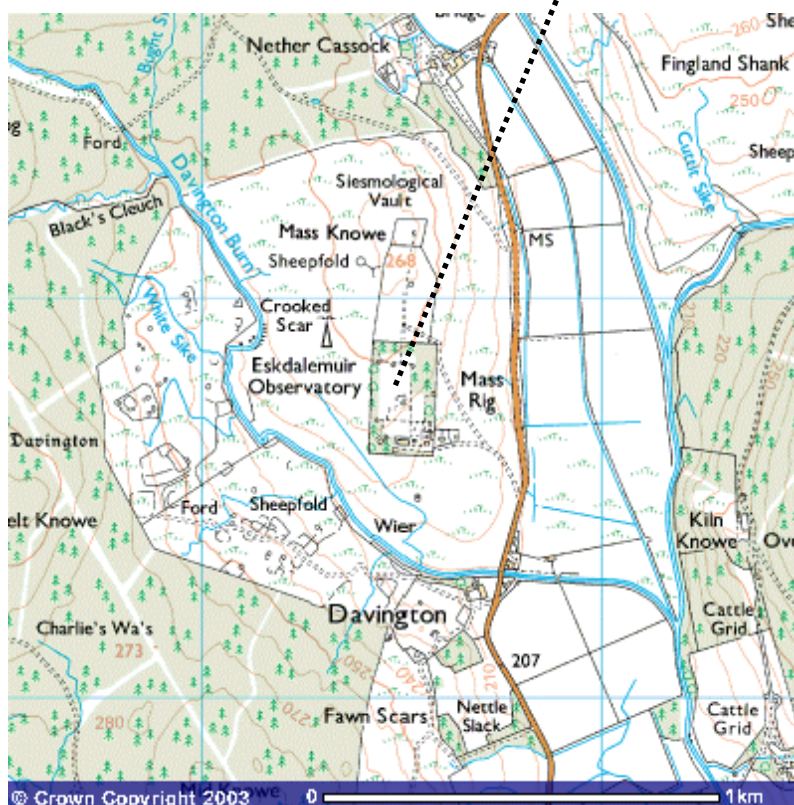


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Figure 5.1: Location plan

5.2.2 Experimental Design

Eight different types of tipping bucket rain gauge were tested, which for the purpose of experimental design were considered as the treatments. These are described as types 1 to 8 for reasons of confidentiality. These were compared against a control gauge (meteorological office 5" gauge read daily) at a vertical height of 12". Supplementary control data will be obtained from 2 extra meteorological office 5" gauges, one pit mounted and one turf wall. The treatments were as follows:

Treatment 1	type 4 (stainless steel aerodynamic gauge)
Treatment 2	type 7 (plastic aerodynamic gauge)
Treatment 3	type 1 (conventional gauge)
Treatment 4	type 8 (conventional gauge)
Treatment 5	type 5 (conventional gauge)
Treatment 6	type 3 (conventional gauge)
Treatment 7	type 2 (conventional gauge)
Treatment 8	type 6 (conventional gauge, all stainless steel)
Treatment 9	Control

The gauges were laid out in a randomised block design with each of the treatments and controls replicated three times (Figure 5.2 and Table 5.1)

Table 5.1: Randomisation

Gauge position No	Block No	Treatment no
1	1	7
2	1	8
3	1	4
4	1	1
5	1	5
6	1	Control
7	1	2
8	1	3
9	1	6
10	2	3
11	2	Control
12	2	1
13	2	2
14	2	6
15	2	5
16	2	7
17	2	4
18	2	8
19	3	7
20	3	2
21	3	8
22	3	3
23	3	6
24	3	Control
25	3	4
26	3	5
27	3	1

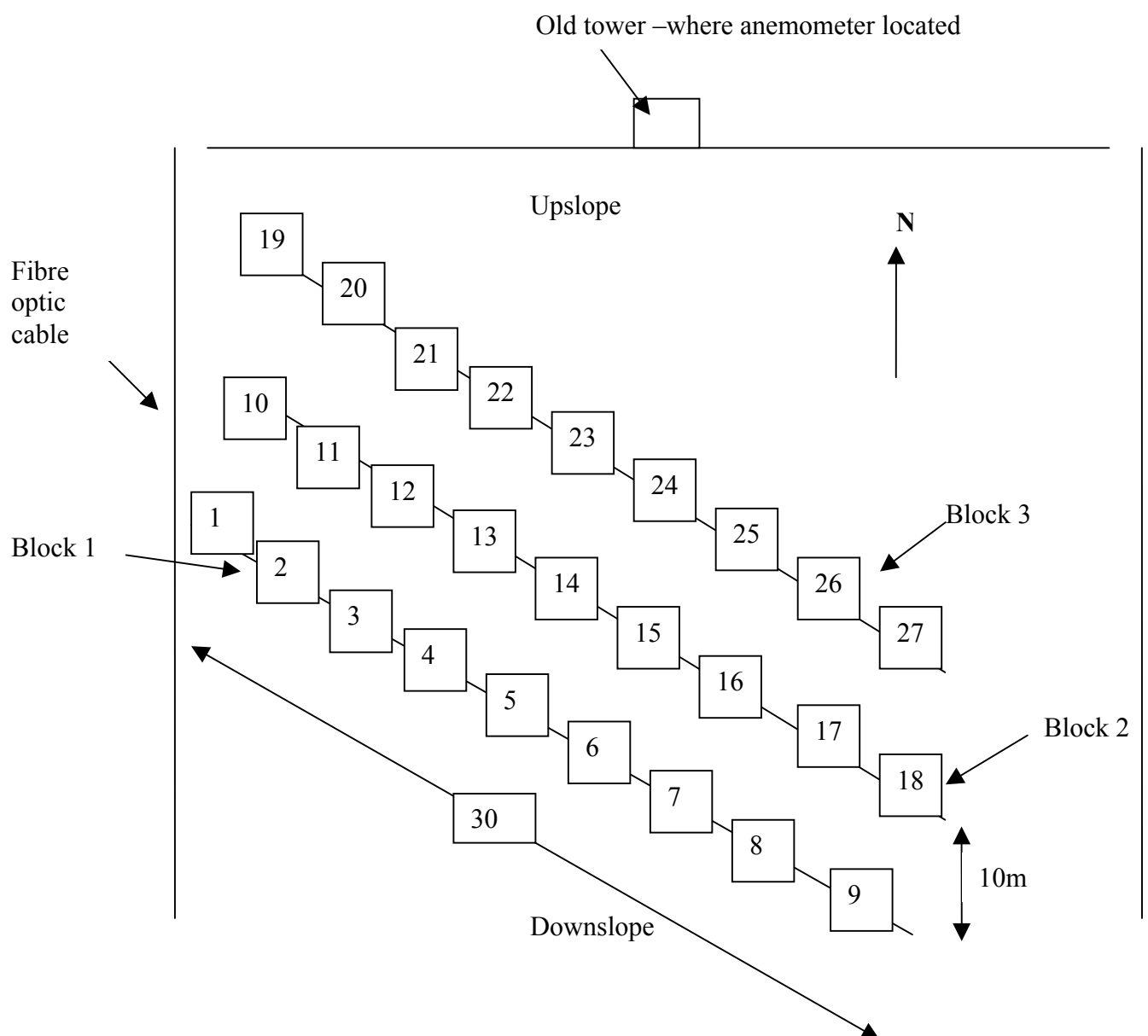


Figure 5.3: Layout of trial site

Each tipping bucket gauge was mounted on a precast concrete paving slab, which itself was bedded on a sand and cement mixture to ensure stability. All gauges were installed following standard Environment Agency procedures and also taking account of any manufacturer specific instructions. Each block of raingauges was connected to a separate Newlog datalogger that recorded the exact time when a tip was measured on each of the gauges.

5.2.3 Measurements

A continuous record was kept, on a NEWLOG datalogger, of each tip recorded on each raingauge. The rainfall recorded by the standard meteorological office 5" gauges, including exposed and those in pit and turf wall installations, was measured at 1400

hours each day every day using standard meteorological office procedures. Data describing wind speed (average and gust) and direction, at hourly intervals were provided by the close by climate station (a 2m high tower 15m from block 1) operated by the Meteorological Office. Temperature and relative humidity data were provided from the measuring facilities some 300m away at the observatory

The performance of the gauges following snowfall was compared using a simple scale was used to assess the amounts remaining in all the gauges: (0=Clear, Tr=Trace, S=Slight, M=Moderate, L=Large). A record was also kept of any faults that developed with individual gauges or specific operational problems encountered

5.2.4 Statistical Analysis

A multiple comparison test (Dunnet, 1970) was used to determine whether the treatments were significantly different from the controls and Duncans multiple range test (Duncan, 1955) was used to determine whether the differences between pairs of means were significant. Regression analysis was undertaken to determine whether a relationship between gauge catch and other variables could be found. Analyses were undertaken using either Statistica™ or Minitab™ packages.

5.2.5 Summary of climate data recorded at the observatory

The climate data recorded outside the main observatory building are reported as these can be compared to long term averages and provide a contextual background against which the data from the trial can be considered.

Rainfall recorded at the Observatory

Trial year	1583.8mm
1911 - 2001 Average	1567.6mm

'Wet Days' (Number of days with 1.0mm or more)

Trial year	191 days
1911 - 2001 Average	180 days

Intensity (mm per 'Wet Day')

Trial year	8.29mm
1911 - 2001 Average	8.71mm

Snowfall

Days with sleet or snow reported

Trial year	21
1911 - 2001 Average	56

Sunshine

Trial year	1290.1 hours
1911 - 2001 Average	1190.2 hours

Mean Temperature

Trial year	7.97°C
1911 - 2001 Average	7.10°C

The year of the trial period was unremarkable when compared to the past 12 years or so, with above average temperatures and reduced snow frequency. The most significant rainfall event was undoubtedly 21st/22nd October, when between 65 and 70mm were recorded by the check gauges in 24 hours. In all, the period 20th - 27th October produced about 170mm.

Wind direction was in line with long term averages, being predominantly from the Southwest. Similarly, wind speeds were very much in line with the past few years, that is somewhat lower than historically due to the shelter effects of local afforestation.

5.3 Results

5.3.1 Overall performance of gauges

The total rainfalls measured over the study period (1/06/2002 to 31/05/2003) by the check gauges in each block are presented below in table 5.2. The largest catch of rainfall was measured by the turf wall gauge, with the pit gauge recording 1.5% less. The mean catch recorded by the 3 unsheltered meteorological office 5" gauges (control gauges) was 4.4% less than the turf wall.

Table 5.2: Overall catches (June, 2002 to May, 2003 inclusive) from manually read gauges

Block 1 (Lower)	Block 2 (Middle)	Block 3 (Upper)	Turf Wall	Pit
1556.6	1551.0	1547.1	1622.6	1598.6

The total rainfall recorded at the observatory was less than the total of 1622 mm recorded at the turf wall check gauge on the trial site. The figure for the trial site would have been considerably higher still had it been possible to measure the accumulation of snow which fell in early February.

To allow a comparison of the raw catch data from the TBRs against total catch by the check gauges individual totals were calculated for the study period. A total was produced for each TBR for the days when that specific gauge was operational, a total was also produced for same time period using the meteorological office 5" gauge (control gauge) in the same block. The totals derived in this way are presented in figures 5.3a to 5.3c and an overall summary is presented in table 5.3.

Table 5.3: Summary of overall mean gauge performance

Gauge	type 7	type 4	type 1	type 8	type 5	type 3	type 2	type 6
%	94.6	91.3	83.8	89.8	84.1	76.9	81.3	78.9
Control catch recorded								

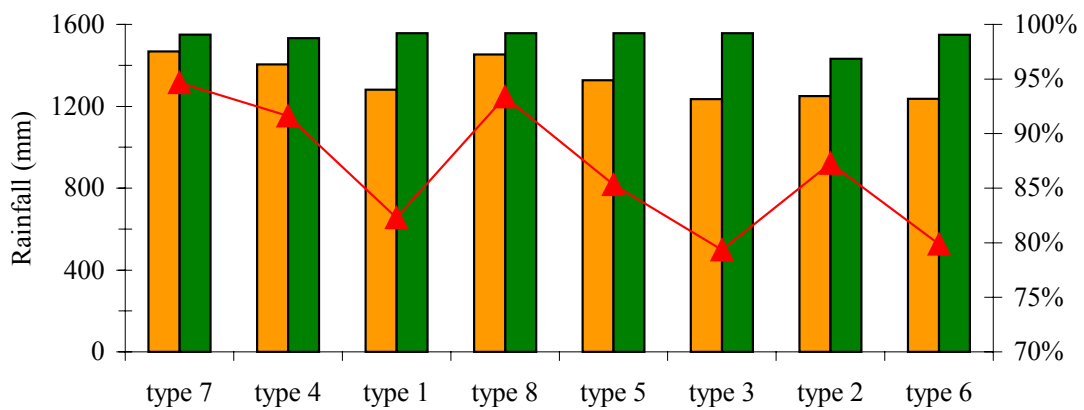


Figure 5.3a: Comparison of tipping bucket totals (1 June 2002 to 31 May 3002) against meteorological office 5" gauge total (block 1).

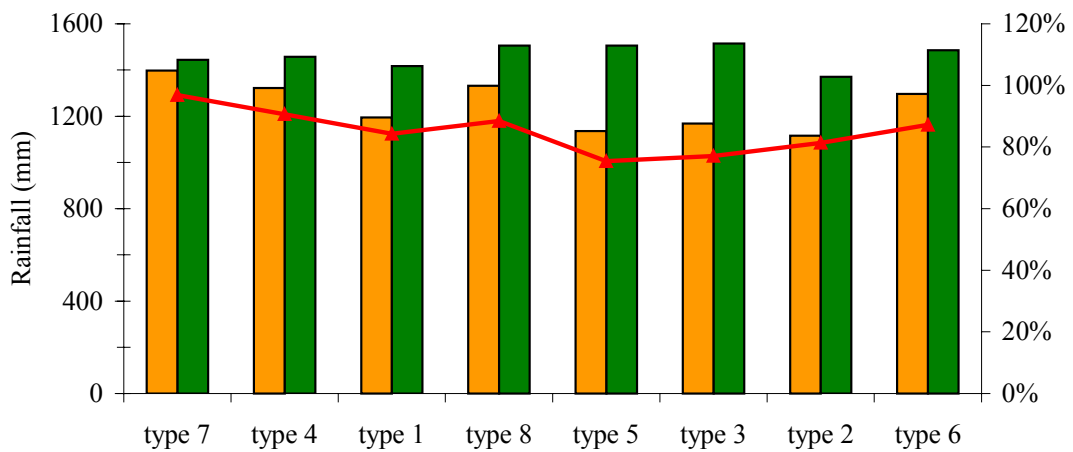


Figure 5.3b: Comparison of tipping bucket totals (1 June 2002 to 31 May 3002) against meteorological office 5" gauge total (block 2).

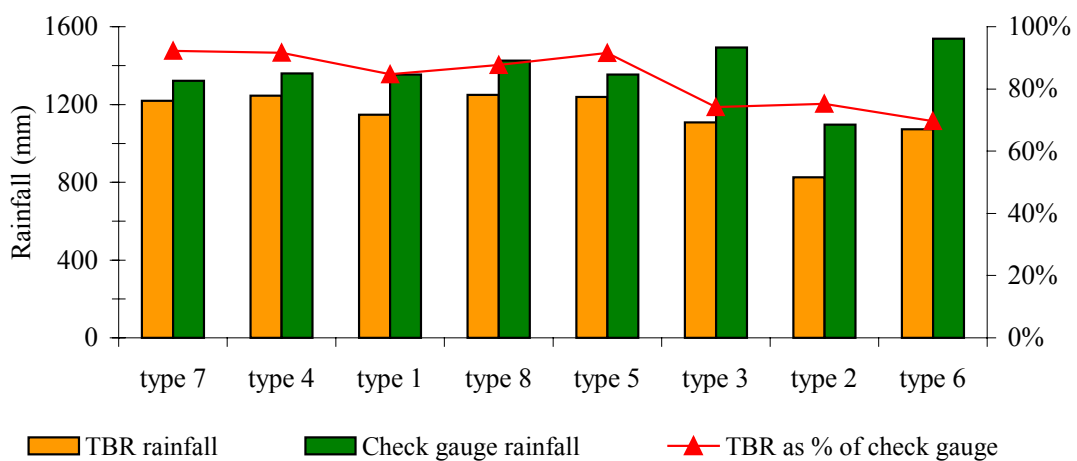


Figure 5.3c: Comparison of tipping bucket totals (1 June 2002 to 31 May 2003) against meteorological office 5" gauge total (block 3).

The first, and most striking fact that can be noted from this data is that, on average, none of the TBRs came within 5% of the check gauge totals. It is also immediately evident that the best performing gauges were those with an aerodynamic shape. Detailed consideration of the data presented in the graphs was undertaken by ranking the gauges in order of performance (table 5.4). This showed that while the type 7 had consistently the highest catch compared to the controls that there was little to choose between the type 8 and the type 4 in two out of three blocks. The type 3 always stood out as having a low catch in all three blocks and the type 6 in two out of three. The close agreement (<1%) between the Met Office 5" check gauges annual totals in blocks 1,2 and 3 should also be noted.

Table 5.4: Rank order of gauge catches

Rank	Block 1		Block 2		Block 3		Overall	
	Gauge	% control catch	Gauge	% control catch	Gauge	% control catch	Gauge	% control catch
1	type 7	94.7	type 7	96.9	type 7	92.3	type 7	94.6
2	type 8	93.4	type 4	90.7	type 4	91.6	type 4	91.3
3	type 4	91.6	type 8	88.5	type 5	91.6	type 8	89.9
4	type 2	87.3	type 6	87.2	type 8	87.7	type 5	84.1
5	type 5	85.3	type 1	84.3	type 1	84.7	type 1	83.8
6	type 1	82.3	type 2	81.4	type 2	75.2	type 2	81.3
7	type 6	79.9	type 3	77.1	type 3	74.2	type 6	78.9
8	type 3	79.3	type 5	75.4	type 6	69.7	type 3	76.9

5.3.2 Relative performance of different gauge types

To carry out a true comparison between the gauges a subset of the data was produced which produced an overall total for daily means, which met the following conditions.

Data available for all three replicates of all gauges

Mean of all three meteorological office 5" gauge > 5mm (5mm selected to avoid influence of drizzle)

No snow effects noted by observers

The relative performance of each of the gauge types (including the meteorological office 5") expressed as mean percentage of the rainfall recorded by the pit and turf wall gauges (based on the subset described above) are presented in table 5.5 for the whole year, winter (November to March) and non winter periods. The use of data expressed as a proportion of the pit and turf wall gauges, rather than as a proportion of the control, had the additional advantage of allowing the impact of aerodynamic effects on the meteorological office 5" gauge to be quantified and removed this interaction from any assessment of the TBRs. The catch measured by the type 7 (plastic aerodynamic gauge) corresponded most closely to that measured by the standard meteorological office 5" gauge in all three cases, followed closely by the type 4 (stainless steel aerodynamic) and type 8 gauges. The next highest catch (4th in rank order) was consistently recorded by the type 5 gauge. Fifth and sixth places in rank order were by the type 1 and type 2 gauges when either the whole year or winter data were considered. However in the case of the non winter data 6th position was occupied by the type 6 gauge, which shared lowest rank position with the type 3 based on the whole year data and was the worst performer over the winter period.

Table 5.5: Mean catch for each gauge type expressed as a proportion of the pit/turf wall gauges

	type 7	type 4	type 1	type 8	type 5	type 3	type 2	type 6	Met. Office 5"
Whole year	92	88	81	87	82	75	79	75	96
November to March	90	85	78	85	79	73	78	68	95
April to October	94	91	84	90	85	78	81	82	98

The mean catch for each gauge and the 95% confidence intervals are presented in figures 5.4a, to 5.4c. It can be seen from this that the confidence interval around the mean catch from the meteorological office 5" gauge is much tighter than around any of the other gauges. Further, the confidence intervals around the means of all different types of gauges are larger during the winter period, i.e. in winter the agreement between gauges of the same type is less good.

Dunnett's test showed that the mean catch over the whole period from the meteorological office 5" gauge was significantly greater than that from the tipping bucket gauges (type 7 ($p < 0.05$) and all other gauges ($p < 0.0001$). In the non winter period the catches from all the tipping bucket rain gauges was less than that from the meteorological office 5" gauge ($p < 0.0001$). In contrast when the winter period only was considered the catch from the type 7 gauge was not significantly different from the meteorological office 5" gauge ($p > 0.05$) whereas the catches from all the other tipping bucket gauges were significantly less ($p < 0.0001$).

Duncan's test was used to allow comparison between individual gauges as opposed to a simple comparison of all gauges against a control. The results of this are presented in Tables 5.6a to 5.6c. This test allows the gauges to be allocated to groups, or populations, with catches that are significantly different. For example the test shows that the standard meteorological office 5" gauge and the type 7 gauges both have mean catches that are statistically different from each other and the rest of the gauges. The populations to which gauges belong are shown in table 5.7, in which groups or populations are placed in order of the magnitude of the mean catch.

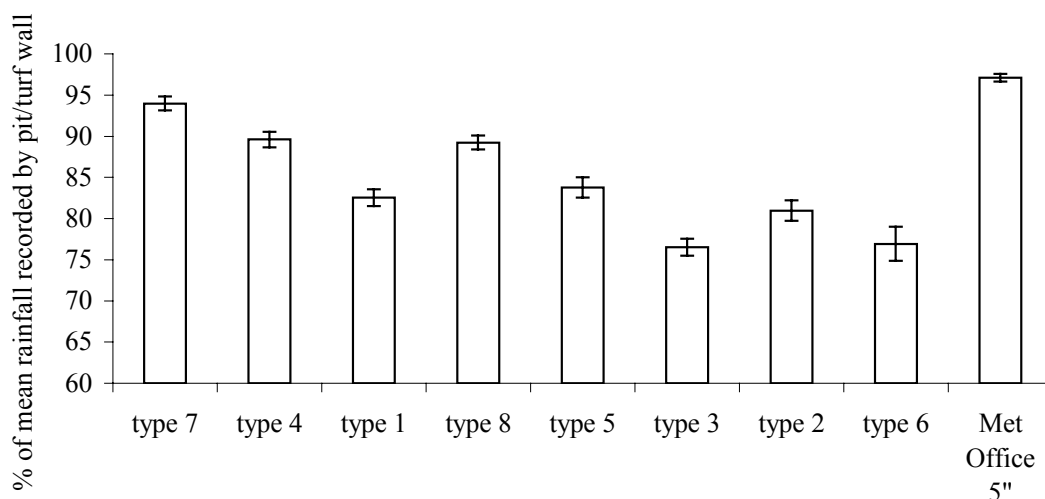


Figure 5.4a Percentage of rainfall recorded by pit and turfwall gauges – all year

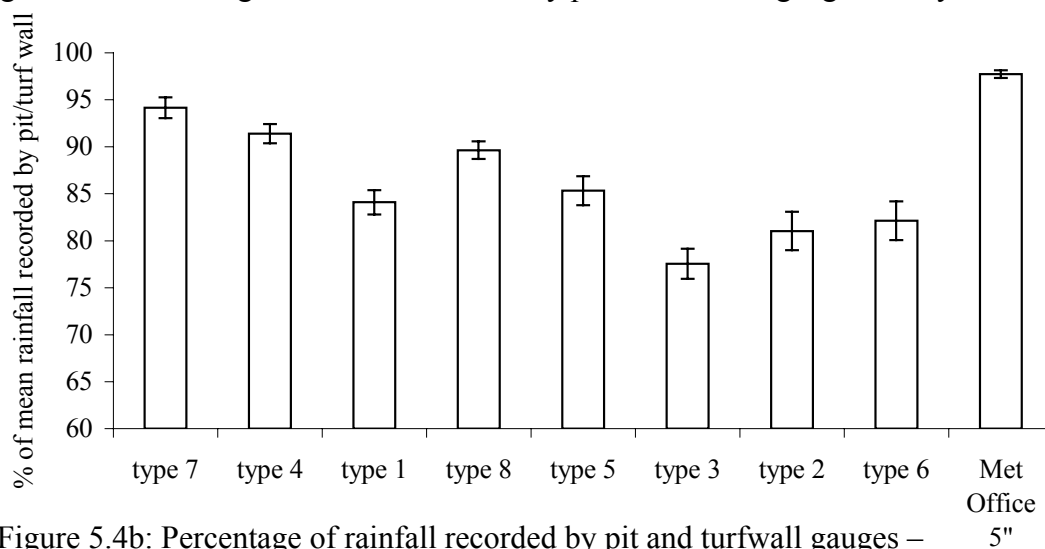


Figure 5.4b: Percentage of rainfall recorded by pit and turfwall gauges – non winter

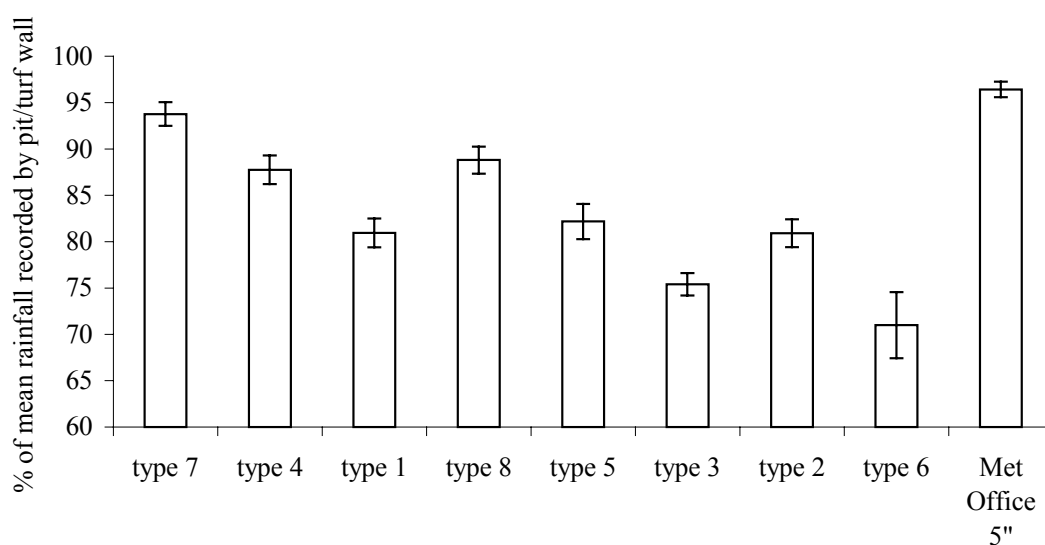


Figure 5.4c: Percentage of rainfall recorded by pit and turfwall gauges – winter only

Table 5.6a: Duncans test – Probabilities for Post Hoc tests - whole season

Gauge	type 7	type 4	type 1	type 8	type 5	type 3	type 2	type 6	Met. Office 5"
Mean	93.97	89.61	82.54	89.23	83.79	76.52	80.97	76.93	97.12
type 7									
type 4	0.000009*								
type 1	0.000004*	0.000003*							
type 8	0.000011*	0.650119	0.000011*						
type 5	0.000003*	0.000011*	0.128894	0.000009*					
type 3	0.000005*	0.000004*	0.000003*	0.000004*	0.000004*				
type 2	0.000004*	0.000004*	0.056145	0.000003*	0.000884*	0.000011*			
type 6	0.000004*	0.000004*	0.000011*	0.000004*	0.000003*	0.61469	0.000010*		
Met. Office 5"	0.000139*	0.000011*	0.000004*	0.000003*	0.000004*	0.000001*	0.000004*	0.000005*	

Table 5.6b: Duncans test – Probabilities for Post Hoc tests – winter

Gauge	type 7	type 4	type 1	type 8	type 5	type 3	type 2	type 6	Met. Office 5"
Mean	93.77	87.76	80.94	88.80	82.17	75.41	80.91	70.99	96.42
type 7									
type 4	0.000014*								
type 1	0.000004*	0.000011*							
type 8	0.000107*	0.417353	0.000003*						
type 5	0.000003*	0.000020*	0.336903	0.000011*					
type 3	0.000004*	0.000004*	0.000032*	0.000004*	0.000003*				
type 2	0.000004*	0.000003*	0.981116	0.000004*	0.357351	0.000025*			
type 6	0.000005*	0.000004*	0.000003*	0.000004*	0.000004*	0.000558*	0.000011*		
Met. Office 5"	0.038016*	0.000003*	0.000004*	0.000011*	0.000004*	0.000005*	0.000004*	0.000001*	

Table 5.6c: Duncans test – Probabilities for Post Hoc tests – non-winter

Gauge	type 7	type 4	type 1	type 8	type 5	type 3	type 2	type 6	Met. Office 5"
Mean	94.17	91.40	84.10	89.64	85.34	77.54	81.03	82.14	97.73
type 7									
type 4	0.005504*								
type 1	0.000004*	0.000003*							
type 8	0.000019*	0.078328	0.000011*						
type 5	0.000003*	0.000011*	0.213703	0.000025*					
type 3	0.000005*	0.000004*	0.000003*	0.000004*	0.000004*				
type 2	0.000004*	0.000004*	0.003059*	0.000004*	0.000034*	0.000473*			
type 6	0.000004*	0.000004*	0.049564*	0.000003*	0.001922*	0.000017*	0.269464		
Met. Office 5"	0.000363*	0.000011*	0.000004*	0.000003*	0.000004*	0.000001*	0.000005*	0.000004*	

Table 5.7: Allocation of gauges to significantly different populations using Duncans test, in order of decreasing performance

Group	Whole year data	Winter data	Non-winter data
1	Met. Office 5"	Met. Office 5"	Met. Office 5"
2	type 7	type 7	type 7
3	type 4 & type 8	type 4 & type 8	type 4 & type 8
4	type 5/ type 1	type 5/ type 1/type 2	type 5/type 1
5	type 1/type 2	type 3	type 6/type 2
6	type 6/type 3	type 6	type 3

Clearly the type 7 stands out as the gauge that had catch that that was closest to that of the standard meteorological office 5" gauge, but it caught significantly less ($p < 0.05$). The type 4 gauges and the type 8 gauges had catches that were not significantly different whatever period is considered but which have a significantly lower catch again than the type 7. When the whole year data set is considered group 4 contains type 5/type 1 and group 5 type 1/type 2. This occurs because the confidence intervals around the means for type 5 and type 1 overlap and type 1 and type 2 overlap but the type 2 and type 5 do not. In winter there is no significant difference ($p > 0.05$) between the catch of the type 1, type 2 or type 5 gauges whereas in the non-winter period only the type 5 and type 1 are indistinguishable ($p > 0.05$). In the non-winter period the catch of the type 2 was not significantly greater than that of the type 6 ($p > 0.05$) forming a group with the 5th lowest catch. However, when considered over the whole year the type 6 and the type 3 gauges had similar catches ($p > 0.05$) but which were significantly lower than the type 1/type 2 group ($p < 0.05$). When the winter period was considered separately the type 6 caught significantly less than the type 3 ($p < 0.05$) with the converse being true in summer.

In practical terms the groups can reasonably be amalgamated together as follows:

Met. Office 5" > type 7 > type 4 & type 8 > type 1, type 5, type 2 > type 3 & type 6.
 (94.2%) (91-89%) (84-81%) (78-76%)

5.3.3 Impact of wind and temperature on gauge performance

The data presented earlier in table 5.5 are repeated overleaf in table 5.8 for ease of reading and show a seasonal comparison of TBR gauge performance compared to the pit and turf wall gauge totals. What is immediately obvious for all gauges is that there is a seasonal impact on gauge performance. When the totals for the whole year are compared with the winter (November to March) and summer (April to October) periods, the winter totals are observed to be below that of summer, by on average 4-5%. This trend is also apparent on the standard Met Office 5" gauge, which shows winter readings 3% less than summer readings. That the trend is observed in the Met Office 5" control gauges is of considerable importance as the only difference between these gauges and the Met Office 5" pit and turf wall gauges is there aerodynamic exposure. Thus the study has shown that in the winter period, which has more months when wind speeds (Figure 5.5) and gust speeds tend to be higher, the standard Met Office 5" gauges catch less rain.

This shows that during the study period there was a definite seasonal effect on gauge performance amounting to on average a 4-5% lower reading for winter than summer.

Table 5.8: Mean catch for each gauge type expressed as a proportion of the pit/turf wall gauges (Table 5.5 Repeated)

	Met. Office 5"	type 1	type 2	type 3	type 4	type 6	type 5	type 7	type 8
Whole year	96	81	79	75	88	75	82	92	87
November to March	95	78	78	73	85	68	79	90	85
April to October	98	84	81	78	91	82	85	94	90

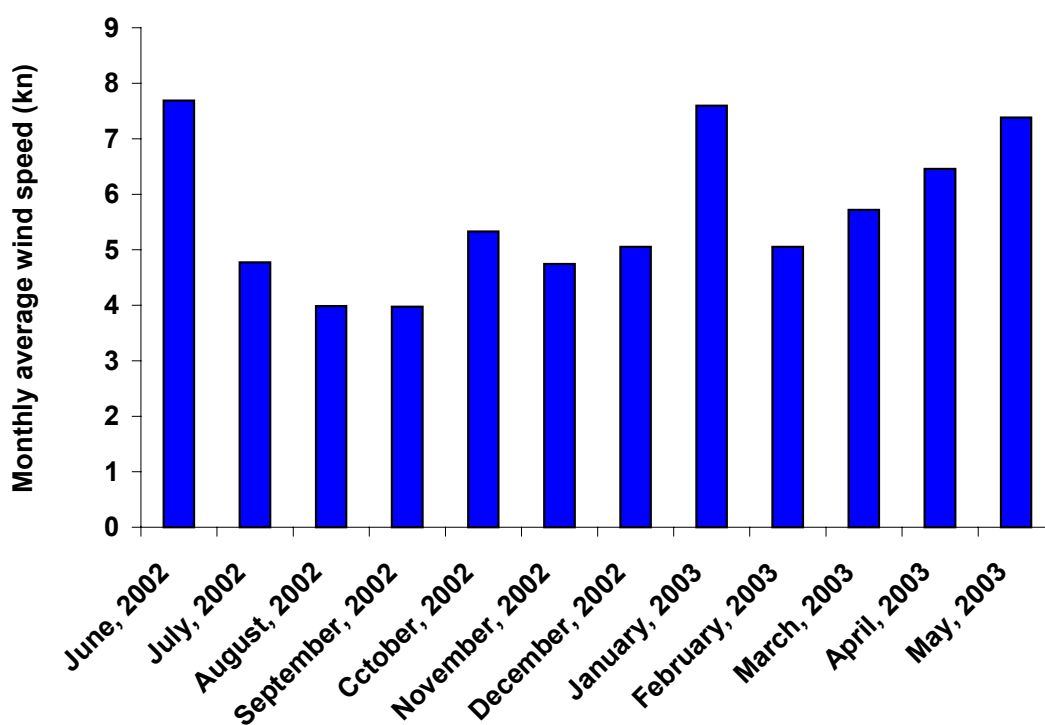


Figure 5.5: Monthly average wind speed

Further detailed analyses were undertaken to determine relative importance of aerodynamic effects, rainfall intensity and snow catch performance. Regression techniques were used to try and determine whether the temporal variation in gauge performance could be ascribed differences in ambient conditions at the time of measurement i.e., differences in wind velocity or temperature. The dependant variable was the relative catch compared to the pit wall and turf gauges and the independent variable were daily mean wind speed, daily mean hourly gust and daily mean temperature, all calculated for the time it was raining in each day. This was achieved by identifying those hours during which tips were recorded on any TBR, and then carrying forward to the means only climate data associated with those hours. This approach is necessarily a compromise as rain may not fall for the entire hour, but this approach was taken, as it seemed unreasonable to use a simple daily wind speed but the resolution at which climate data were available did not permit a more detailed approach

The coefficients obtained from the regression analysis, and the R^2 values for the relationships, are presented in Appendix A for whole year, winter (November to March) and non-winter periods respectively. All regression equations were of the form:

$$y = c + mx$$

where

y is the Proportional catch

x is the meteorological variable in question

m is the slope of the regression line

c is a constant

All the intercept values derived by the regression analysis were significantly greater than zero ($p < 0.05$), but this is as much a reflection of their magnitude as anything else and some of the slopes were significantly different from zero. However, and more crucially, all the R^2 values for the relationships were very small (< 0.2) which means that very little inference can be drawn from the equations as they explain very little of the variation in the gauge catch.

However, it is interesting to note that when windspeed or gust speed are the dependant variables and winter or all year data are considered only the regression line for the type 7 has a small positive slope. This indicates that the type 7 gauges are catching the same, or more rain at various windspeeds whereas the other gauges show a decrease in catch with increasing windspeed). Patterns within the non-winter data, when there is likely to be less wind, were less clear. Negative slopes dominated the regression lines between catch and temperature, i.e. as temperature increased catch tended to decrease. The only positive slopes being that for the type 4 (nearly flat) and the type 6 which was not only positive but had the largest magnitude of any of the gauges.

Further regression analyses were undertaken using the difference between mean wind speed and mean gust speed (a possible index of wind variability) and multiple regression of wind, gust and temperature were undertaken. These relationships were as weak, or weaker than, the simple regressions and are therefore not presented.

Summary plots of the regression lines based on all three replicates of each gauge are presented in figure 5.6 for whole year, winter and non-winter datasets respectively, and the parameters describing these relationships are available in Appendix A. It can be seen from these graphs that the gauge which appears to be least influenced by wind speed is the type 7, with even the meteorological office 5" gauge showing a predicted decline in catch at higher windspeeds. Interestingly, only the relationship between wind speed and relative catch for the meteorological office 5" gauge had an intercept, which was close to 100%. Assuming a linear relationship between catch and windspeed the intercept should tend to 100% for all gauges at zero wind, if wind is the main influence. However, whether this difference is real or a function of the considerable variation in response between replicates is open to question. The considerable variation between replicates is clearly a major cause of the low % variance accounted for by the overall relationships derived from the observed data. Additionally, the assumption that the relationship is linear is possibly not valid.

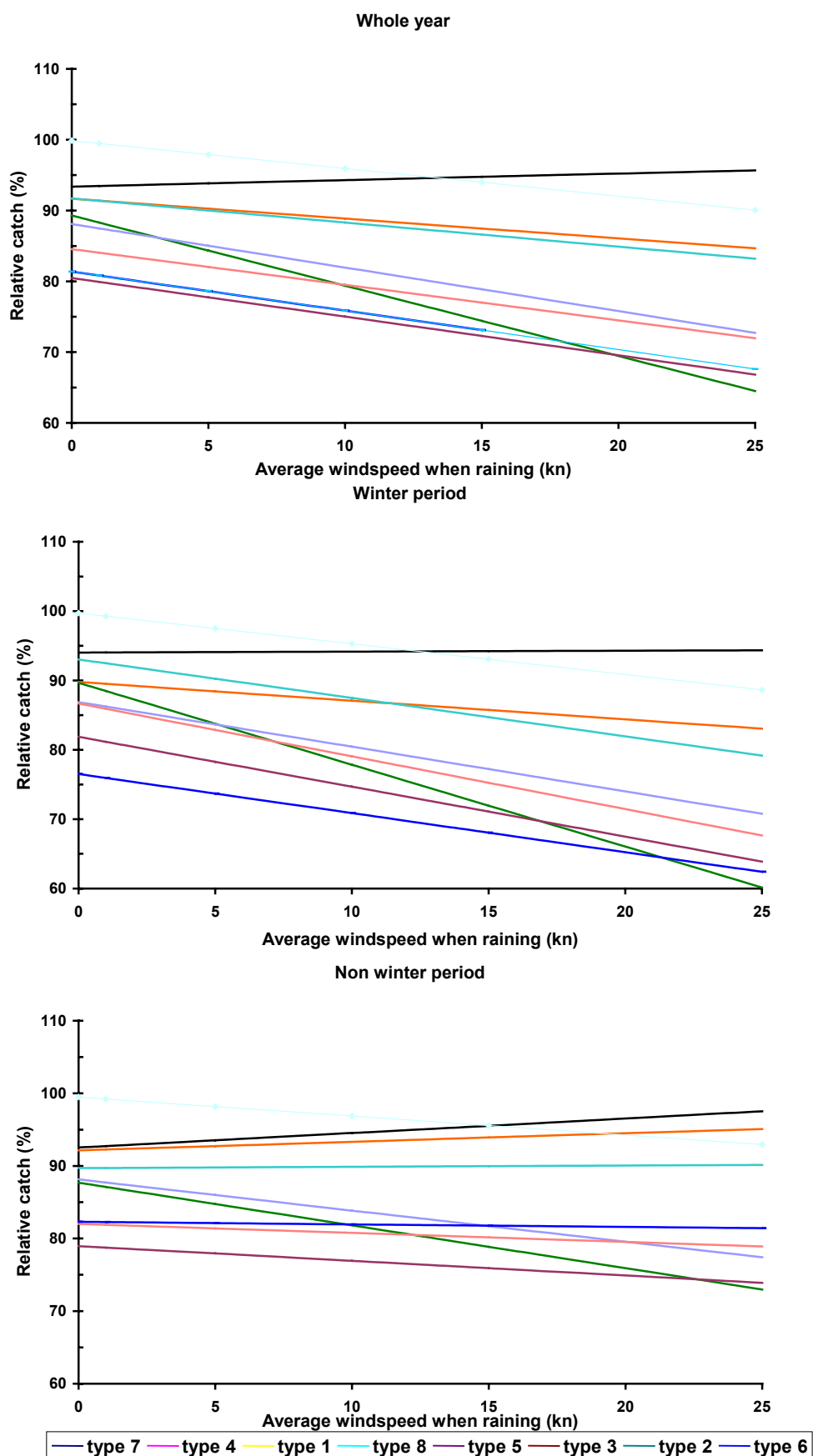


Figure 5.6: Relationships between relative catch (%) and average wind speed during hours when rainfall is recorded

Consideration of the mean relative catches (whole season for each gauge), presented in table 5.9, identifies that, for a given gauge, in most cases the catch is higher in Block 1 than Block 2 or Block 3 and similarly Block 2 catch tends to be higher than Block 3. This raises the issue of whether the exposure, and hence wind speed varies significantly across the site.

Table 5.9: Relative catches (%) of individual gauges (whole year data)

	Met. office 5"	type 1	type 3	type 2	type 4	type 5	type 6	type 7	type 8
% catch block 1	97.4	81.7	79.1	87.1	90.3	83.5	79.8	94.5	93.3
% catch block 2	97.2	83.1	76.9	80.6	89.6	75.7	86.3	96	87.3
% catch block 3	96.8	83.3	73.9	74.8	89.4	91.1	67.2	91.7	87.2

5.3.4 Influence of rainfall intensity on catch measured by the TBRs

In order to determine whether the low catches recorded by the TBRs were a consequence of water lost during the time taken for the bucket to tip the data was recalculated incorporating a dynamic correction. This used the equation between rainfall intensity and % error that was determined in the laboratory phase of this study (Hodgkinson, 2002). The equation used was that developed from combining datasets from all the gauges. The equation used was $Y = 0.779 - 0.1278X + 0.000408X^2$ where Y = % error and X = intensity. This was implemented at a 5-minute time step and was run on the whole years data. Data were only corrected where intensity was such that under reading was expected due to large uncertainty in the equation at lower intensities. The change in rainfall recorded by each of the TBRs is presented in table 5.10

Table 5.10: Changes % in measured rainfall due to implementation of a dynamic correction factor at a 5 minute timestep

Gauge	type 7	type 4	type 1	type 8	type 5	type 3	type 2	Type 6
Block 1	0.10	0.11	0.67	0.12	0.12	0.11	0.08	0.14
Block 2	0.13	0.10	0.11	0.14	0.12	0.12	0.07	0.34
Block 3	0.08	0.07	0.07	0.13	0.09	0.08	0.01	0.12

A comparison was also made, using a short period of data when large rainfall occurred, and intensities reached ca. 15 mm hr⁻¹, between a dynamic calibration based on a 5 minute time step and correction based on the time of tip. The results (figure 5.7) show that no significant improvement was obtained by the time of tip approach and that the differences between the TBRs and the manually read gauges were much greater than any dynamic corrections

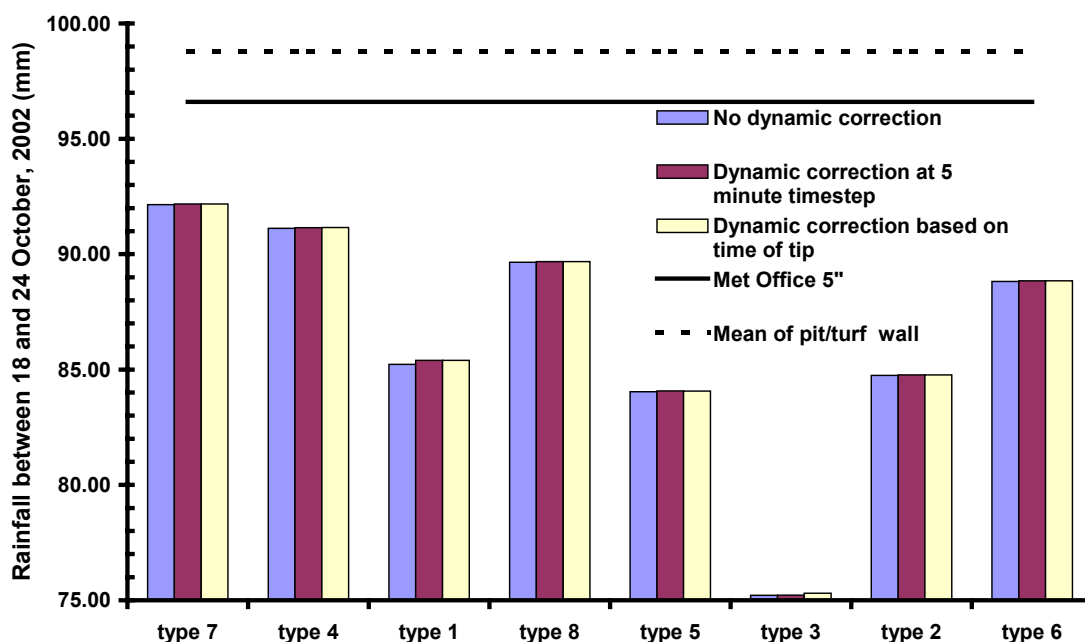


Figure 5.7: Comparison between no dynamic correction and correction at 5 minutes or time of tip

The fact that small only increases in catch were brought about by implementation of the dynamic calibration were due to the fact that rainfall intensities were only in excess of the amount (10mm hour) for relatively short periods during the study period (Table 5.11)

Table 5.11: Cumulative period (minutes in year) during which intensities were over 10mm hr⁻¹ in any 5 minutes maximum duration possible per year 525600 hours.

Gauge	type 7	type 4	type 1	type 8	type 5	type 3	type 2	type 6
Block 1	320	325	365	330	300	290	275	300
Block 2	240	295	265	285	270	250	260	310
Block 3	270	200	230	285	275	190	165	320

5.3.5 Performance following Snow

Overnight snow 2nd/3rd, of January 2003 followed by maximum temperature around zero

presented an excellent opportunity to compare the length of time unmelted snow remained in the various types of gauges. The results are presented in table 5.12.

Table 5.12: Speed of snow melt January 3, 2003

Gauge	Block 1	Block 2	Block 3	Comments
type 7	L	L	L	Very poor retains snow longest
type 1	M	M	M	Poor
type 8	S	S	S	Good
type 4	S	S	Tr	Good
type 2	0	0	0	Best performer all gauges clear
type 6	S	M	M	Average
type 3	Tr	Tr	S	Good
type 5	S	M	M	Average

Reliability and performance in the field

Only a limited number of faults were identified during the field test and no failure of major components such as reed switches occurred. Gauge specific problems identified are reported below

type 7.

Leveling found to be difficult due to plastic installation screws and lack of an external bubble. Algal growth was found to occur on buckets and filters tended to need regular cleaning

type 4

No specific faults reported

type 1

No specific faults reported

type 8

No specific faults reported

type 5

Filter reported to both blow away and retain water at other times.

type 3

Lacquer coating started to come off one bucket by July 02 (deployed in the field Jan. 02)

type 2

Buckets found to lock in central (balanced position)

type 6

No specific faults reported

5.4 Discussion

Comparison of the catches from the TBRs with either that of the plain meteorological office 5" check gauge or the pit/turf wall gauges showed surprisingly large variations with the TBRs recording consistently less rain fall than the manually read gauges. In the case of the type 7 and type 4 this contrasts to the findings of (Porter, 2000) who reported that the catch of the aerodynamic gauges tended to exceed that of the meteorological office 5" gauge. However, from the standpoint of the other gauges tested, the data reported by (Porter, 2000) generally supports the finding of this study, i.e. that TBRs catch less rain. Of the gauges tested by (Porter, 2000) the type 1 gauge performed particularly poorly being out of agreement with the check gauge by more than 5% for 36% of the time which is consistent with the findings of this study. However, in some periods during the summer (Porter, 2000) found that the TBRs caught more rain than the meteorological office 5" check gauge which is at variance with the results reported on here. The TBR with the catch closest to the pit/turf wall gauges or meteorological office 5" check gauge was the type 7 plastic aerodynamic rain gauge; this tends to suggest an aerodynamic effect as the cause of the differences in performance. This is supported by the fact that TBR with the next highest catch was the type 4 also aerodynamic, although its catch was not significantly different from that of the conventionally shaped type 8 gauge.

A seasonal component to catch performance was observed with performance for all TBRs observed to be 4 -5 % lower in winter than summer when compared to the turf and pit gauge controls. The same trend was also observed in the standard Met Office 5" gauges, with recorded 3 % less in winter than summer when compared to the turf and pit check gauges. However, it was impossible to identify a statistically significant wind effect although the slopes of the regression lines suggest that there may be an effect. The question to answer therefore is why no effect could be demonstrated. It is suggested that the failure may be due to differences in scale between the measurement of the wind and what the gauges are exposed too.

Wind velocity was measured at one point (2m) above ground level) whereas each of the gauges are a slightly different height and at different locations relative to the point at which the wind speed is measured. A further issue is that, as the predominant wind comes in to the site it passes across trees, then moorland with say 50cm high vegetation and cut then grass immediately around the gauges. This raises concerns as to whether the wind velocity, and turbulence, may change across the site. Expert advice (Lapworth Pers comm.) suggested that "the change in wind velocity over the whole field is very sensitive at the height of interest. For instance depending on the actual values of the upstream and downstream roughness lengths, then at a height of 0.1m the wind speed might increase by a factor of 2 over the site while at 0.5 metres it might increase by a factor of 10% over the site." To determine whether this effect was real or not it would be necessary implement the actual values of the relevant parameters (i.e. z_0 values, heights of interest, horizontal distances of the rain gauges) into the formula by Panofsky and Townsend (1964) and obtain the results from the analytic theory. It was considered that a detailed evaluation of this effect was beyond the brief of the study. However, it may be that to fully elucidate the interaction between windspeed and catch it may be necessary to use micro anemometers located close to each gauge and at the same type 8vation to ensure that the measured wind speed is the same as that seen by the gauge.

Similarly temperature effects could not be statistically confirmed although interestingly the regression line between type 6 gauge catch and ambient temperature had the greatest slope. The type 6 gauge was identified in the laboratory-testing phase (Hodgkinson, 2002) as being the gauge most influenced by changes in temperature.

The use of a dynamic calibration approach was not found to increase rainfall catch greatly at this site. However, the rainfall intensities encountered were not high enough to frequently trigger the need for dynamic correction, rather it rained steadily for long periods. The low intensity of rainfall that occurred may in itself be a key to the low catches measured by the TBRs as low intensities tend to be associated with small drop sizes which will be more easily deflected by wind or turbulence. However, this does not explain why the TBRs are more affected than the standard meteorological office 5" gauges. The difference in gauge performance may simply be a consequence of the height to width ratio of the respective gauges, with the meteorological office 5" representing less resistance to the wind than the other gauges and hence causing less turbulence and thus achieving a greater catch. The noise in the data, and other issues such as the possibility of changes in wind velocity across the site makes further evaluation of the effects inappropriate.

That the dynamic calibration did not adequately transform the TBR total to that of the manual gauge presents a problem as it did not explain the TBR under-read. Impacts of TBR gauge accuracy, if uncorrected for, will have an impact on the rainfall record as a record. For example in terms of climate change trend analysis, a 4-5 % step change in rainfall measurement accuracy will have a considerable impact on a temporal rainfall analysis of rainfall records.

To overcome this, the following solution is proposed. Every TBR gauge should have a standard Met Office 5" gauge read on a monthly (or of a different frequency depending upon rainfall quantities) basis as part of the standard site configuration. For the equivalent time period, the TBR record should be corrected to match that of the manually read check gauge. This transformation will be simple and linear, which has the benefits of being easy to apply. This approach is supported by the fact that a dynamic calibration based on rainfall intensity did not make a significant difference to the record. Correcting the TBR data in this way will minimize the impact on the long term record of different TBR gauge type characteristics, will ensure BS and Met Office good practice standards, and can be applied to existing historic TBR records also.

Only the type 2 gauge was found to have serious problems in that it locked in the balanced position with water passing into both buckets. This problem also occurred in the laboratory tests (Hodgkinson, 2002) although it was remedied by a visit from a type 2 engineer. This suggests that extra care will need to be taken when setting up these gauges. This problem was not reported by (Porter, 2000) who also tested the type 2 gauge and found it to be particularly reliable; this suggests that the problem may have arisen due to change in construction that has occurred recently. Other practical issues that came to light were greater algal growth on the white plastic gauges (type 7) and the fact that effectively gauge albedo (colour and material) greatly influenced the time the gauges remained blocked after snowfall. It may therefore be worth considering gauges that maximize the gain of energy for the sun when selecting equipment for locations with high snowfall.

5.5 Conclusions

Under the conditions encountered at the study site the best performing TBR gauge caught only 95% of the rainfall recorded by an unsheltered standard Met Office 5" gauge. The range of rainfall catch recorded by the TBR gauges varied from 77 to 95 % of the standard unsheltered Met Office 5" gauges.

The unsheltered standard Met Office 5" gauges caught only 96 % of the rainfall recorded by the standard Met Office 5" gauge in a turf wall configuration. The standard Met Office 5" gauge in a pit configuration recorded 1.5 % less rainfall than the turf wall configuration.

This can be summarized as:

Turf and pit standard	>	Unsheltered standard Met Office	>	Tipping Bucket Raingauge
Met Office 5" gauge		5" gauge		
100 %		96 %		91% to 73 %

(Percentages are expressed as % of combined turf and pit gauge catch)

Under the conditions encountered at the study site an aerodynamic gauge (ARG 100) was the best performing TBR gauge with a catch that was closest to the turf and pit standard Met Office 5" gauge configurations.

A seasonal component to catch performance was observed with overall catch performance for all TBRs 4-5 % lower in winter than summer when compared to the turf and pit standard Met Office 5" gauge configurations. This trend was also reflected in the unsheltered standard Met Office 5" gauge, which recorded 3 % lower in winter than summer when compared to the turf and pit standard Met Office 5" gauge configurations.

No definitive link could be shown between variations in either temperature or wind speed and the rainfall catch of a specific gauge although on a qualitative basis the results suggest that there is a link.

Due to the low rainfall intensities encountered at the study site implementation of a correction using dynamic calibration did not significantly increase measured catch. To overcome the impact on long term records of TBR gauge accuracy, transformation of the TBR total by a the total measured by a standard Met Office 5" gauge over a monthly (or similar) equivalent timebase is recommended.

Further work is required to test the performance of TBRs under a wider range of climatic conditions.

6 NEED FOR FURTHER WORK

If the dynamic calibration curves obtained in the laboratory testing phase are to be applied then these will need to be refined by increased replication using a larger number of gauges to improve confidence in the relationships.

The results obtained from the field trial are only applicable to the climatic conditions pertaining to Eskdalemuir. For the results to be applicable the work, or at least sufficient of it to represent those gauges either used or likely to be used by the Agency, needs to be repeated at a number of locations to represent cross section of range of climatic conditions encountered in England and Wales.

To fully understand the interaction between wind speed and gauge catch future work would need to ensure that the wind profile seen by each gauge is fully captured.

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Appendix A

Title Parameters describing regression relationships between relative rainfall catch and other climatic parameters

Regression analysis based on whole year data

	Mean daily wind speed (when raining)			
	Intercept	Slope	p	R ²
type 7	93.37	0.09	0.56	<0.1
type 4	91.66	-0.28	0.10	<0.1
type 1	89.30	-0.99	<0.000	0.22
			01	
type 8	91.70	-0.34	<0.05	<0.1
type 5	88.10	-0.62	<0.01	0.10
type 3	80.47	-0.55	<0.01	<0.1
type 2	84.54	-0.50	<0.01	<0.1
type 6	81.37	-0.55	<0.5	<0.1
Met. Office 5"	99.86	-0.39	<0.000	0.17
			1	

	Mean daily gust (when raining)			
	Intercept	Slope	p	R ²
type 7	92.16	0.10	0.17	<0.1
type 4	91.85	-0.12	0.13	<0.1
type 1	88.48	-0.32	<0.001	0.12
type 8	90.76	-0.08	0.26	<0.1
type 5	87.10	-0.18	<0.05	<0.1
type 3	80.35	-0.20	<0.01	<0.1
type 2	83.68	-0.14	0.08	<0.1
type 6	80.65	-0.17	0.17	<0.1
Met. Office 5"	99.47	-0.13	<0.01	<0.1

	Mean daily temperature (when raining)			
	Intercept	Slope	p	R ²
type 7	95.94	-0.25	0.18	<0.1
type 4	89.56	0.02	0.92	<0.1
type 1	83.10	-0.01	0.72	<0.1
type 8	89.77	-0.05	0.76	<0.1
type 5	84.24	-0.05	0.82	<0.1
type 3	77.58	-0.11	0.58	<0.1
type 2	83.96	-0.37	0.09	<0.1
type 6	70.66	0.87	<0.01	<0.1
Met. Office 5"	96.24	0.11	0.31	<0.1

Footnote

All intercepts were significantly different from 0 (p<0.0001)

p values refer to whether the slopes of the regression lines significantly different from zero

Regression analysis based on winter data

	Mean daily wind speed (when raining)			
	Intercept	Slope	p	R ²
type 7	94.03	0.01	0.95	<0.1
type 4	89.77	-0.27	0.28	<0.1
type 1	89.65	-1.18	<0.01	0.31
type 8	93.02	-0.55	0.02	0.11
type 5	86.88	-0.64	0.03	0.10
type 3	81.88	-0.72	<0.02	0.20
type 2	86.67	-0.76	<0.01	0.19
type 6	76.51	-0.56	0.15	0.04
Met. Office 5"	99.72	-0.44	<0.01	0.16

	Mean daily gust (when raining)			
	Intercept	Slope	p	R ²
type 7	92.91	0.06	0.56	<0.1
type 4	89.98	-0.11	0.34	<0.1
type 1	89.06	-0.42	<0.01	0.18
type 8	92.23	-0.17	0.13	<0.1
type 5	85.59	-0.18	0.19	<0.1
type 3	80.64	-0.26	<0.05	0.11
type 2	86.22	-0.27	<0.05	0.11
type 6	76.09	-0.20	0.28	<0.1
Met. Office 5"	99.39	-0.15	<0.05	<0.1

	Mean daily temperature (when raining)			
	Intercept	Slope	p	R ²
type 7	95.94	-0.25	0.18	<0.1
type 4	89.55	0.02	0.92	<0.1
type 1	83.10	-0.09	0.72	<0.1
type 8	89.77	-0.05	0.77	<0.1
type 5	84.24	-0.05	0.81	<0.1
type 3	77.58	-0.11	0.58	<0.1
type 2	83.86	-0.37	0.09	<0.1
type 6	70.77	0.87	<0.01	<0.1
Met. Office 5"	96.24	0.11	0.31	<0.1

Footnote

All intercepts were significantly different from 0 ($p < 0.0001$)

p values refer to whether the slopes of the regression lines significantly different from zero

Regression analysis based on non-winter data

Mean daily wind speed (when raining)				
	Intercept	Slope	p	R2
type 7	92.54	0.20	0.41	<0.1
type 4	92.15	0.12	0.59	<0.1
type 1	87.70	-0.59	0.03	0.08
type 8	89.71	0.02	0.93	<0.1
type 5	88.14	-0.43	0.07	<0.1
type 3	78.95	-0.20	0.47	<0.1
type 2	82.02	-0.12	0.68	<0.1
type 6	82.30	-0.04	0.92	<0.1
Met. Office 5"	99.48	-0.26	0.003	0.15

Mean daily gust (when raining)				
	Intercept	Slope	p	R2
type 7	91.39	0.14	0.16	<0.1
type 4	92.21	-0.05	0.62	<0.1
type 1	86.74	-0.16	0.16	<0.1
type 8	88.84	0.06	0.49	<0.1
type 5	87.28	-0.11	0.28	<0.1
type 3	79.309	-0.10	0.41	<0.1
type 2	81.05	-0.01	0.93	<0.1
type 6	80.98	0.06	0.66	<0.1
Met. Office 5"	99.02	-0.07	0.06	<0.1

Mean daily temperature (when raining)				
	Intercept	Slope	p	R2
type 7	97.79	-0.42	0.06	<0.1
type 4	95.08	-0.39	0.07	<0.1
type 1	87.24	-0.34	0.20	<0.1
type 8	90.79	-0.10	0.59	<0.1
type 5	90.18	-0.90	<0.05	<0.1
type 3	79.85	-0.23	0.39	<0.1
type 2	86.08	-0.51	0.07	<0.1
type 6	79.08	0.32	0.34	<0.1
Met. Office 5"	97.47	0.04	0.66	<0.1

Footnote

All intercepts were significantly different from 0 ($p < 0.0001$)

p values refer to whether the slopes of the regression lines significantly different from zero