NOTES AND CORRESPONDENCE

An Improved High-Resolution Raingage

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ABSTRACT

Evaluation of an earlier raingage design based on counting drops formed on the tip of a small-diameter stainless-steel tube shows a defect due to resonant oscillation of the water column in the dropper unit. The defect causes nonlinearity in the drop rate–flow rate relationship, precluding useful integration of the gage output. An improved design is presented which eliminates this defect. Laboratory tests on the new design show linear performance over two orders of magnitude of rainfall intensity with time resolution of better than 5 s and accuracy limited by sampling errors. The new gage is also shown to perform well in field testing.

1. Introduction

Measurement of rainfall intensity I is fundamental to the investigation and interpretation of many physical processes. In order to investigate adequately a wide range of phenomena, such as optical and infrared extinction (Nedvidek et al., 1983; Wang et al., 1978), microwave radio attenuation (Furuhama and Ihara, 1981) and power line transmission loss in rain (Kirkham, 1980), estimates of I with a temporal resolution of at least 10 s are required.

Common commercially available raingages, such as the natural siphon and tipping bucket designs, have insufficient temporal resolution (being typically >1 minute) and are also expensive. A number of designs for rapid-response raingages have been reported in the literature. Those of Semplak (1966) and Seibel (1972) used changes in capacitance due to the flow of collected water to monitor the rainfall rate, while Fullerton and Raymond (1973) used a similar technique that relied on resistance changes. On the other hand, Kirkham (1980) used the flow of collected water to drive a lightweight viscous-damped turbine, while Chauzy and Despiau (1980) converted water flow into airflow, which was directly measured by a flowmeter. Norbury and White (1971) quantized the water flow into a drop stream consisting of drops of known diameter whose number is then counted. The latter method provides an output that may easily be interfaced to digital data acquisition systems, in particular, avoiding the need for variable-time-constant analogue integrators. In addition, the gage unit is relatively simple to construct and has no moving parts. For these reasons the Norbury and White (N–W) design was chosen for evaluation.

2. Evaluation of the Norbury and White raingage

Figure 1, from Norbury and White (1971), shows a section through the dropper unit of their gage. Water input from the funnel enters the bottom of a stilling chamber, passes through a gauze filter, exits the chamber via a small circular channel and is formed into drops on the end of a stainless steel needle.

An evaluation of the dropper unit performance was carried out using the optical disdrometer of Stow and Jones (1981) to measure the size of drops produced. Water input was provided by an adjustable constant-head supply and the drops produced passed through the disdrometer, to be collected in a beaker. Weighing large numbers (~1000) of drops permitted average drop volumes to be measured to about one part in 10^3 and the disdrometer enabled individual drop volumes to be compared to better than five percent during each experiment. The purpose of using the disdrometer was to obtain volume distributions that could be normalized using the results of direct weighing.

Drop rates of up to about 9 Hz (corresponding to ~60 mm h^{-1} rain into a funnel of 200 mm diameter) were possible with the N–W design. However, the performance of the dropper proved erratic, particularly for drop rates in the range 1–2 Hz. At these rates drops were not produced at regular intervals but instead were clustered into groups of two or more. The number of drops in a cluster was generally found to increase with an increase in flow rate. Figure 2 shows that the clustering is associated with drop volume distributions that are multimodal; in this example the drop rate is 1.2 Hz and the volume distribution is trimodal, corresponding to clusters of three drops. The effect of such

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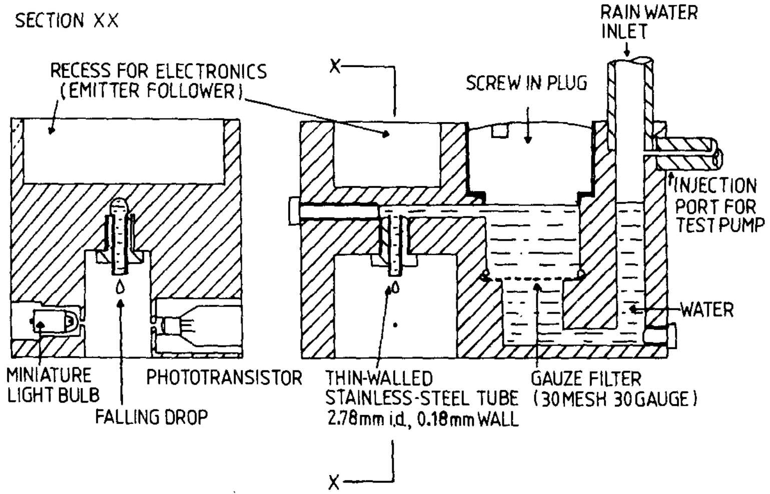

FIG. 1. Cross sections of the dropper gage unit used by Norbury and White (1971); their Fig. 1.

clustering is very serious because it is accompanied by a variation in drop size with rainfall rate, so that the integration of drop counts over periods of time within which the rainfall rate changes will produce data that is in error. The defect limits the use of such a raingage to short integration periods, though the problem is less serious at high rainfall rates because of the large total drop count that can be achieved.

It has been determined that the clustering is caused by oscillation of the water column in the needle and channel. After a drop has detached from the needle, the forces on this column (surface tension and gravitational) are out of balance and oscillation commences. The oscillations are readily visible by eye and have a period of the order 1 s. The oscillations are sufficiently undamped to have significant amplitude at the end of one or two periods. If water is entering the dropper at a fast enough rate, there is enough water in the pendant drop at the maximum of the first or subsequent oscillation for a drop to detach, causing the observed clustering.

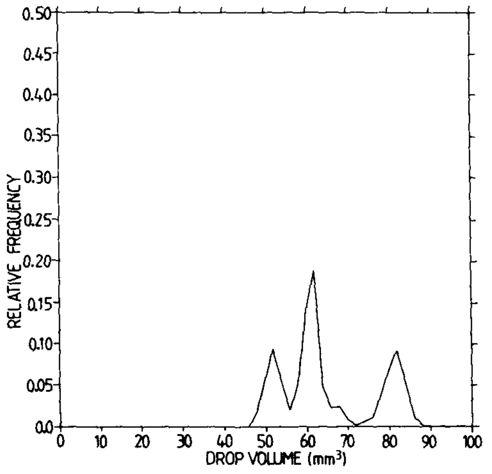

FIG. 2. Drop volume distribution obtained from the N–W raingage for a constant input flow rate; the mean drop rate was 1.2 Hz.

The movement of water in the column and pendant drop is difficult to model in any realistic manner due to the complex fluid flow. Nevertheless, empirical observations showed the frequency of oscillation to be dependent on the length of the water column and its volume and a reduction in these served to increase the oscillation frequency. Restricting the water flow by reducing the column diameter over a small section or introducing glass wool caused damping of the oscillations. However, in order to provide sufficient damping to prevent the clustering, the maximum drop rate achievable was limited to about 4 Hz and this significantly reduced the dynamic range of the instrument.

3. Improved dropper design

The new design of the dropper is shown in Fig. 3. A number of changes have been made to the original design to overcome the problem noted in the previous section. The volume of water in the dropper and the overall length of the water column have been significantly reduced. A gauze insert in the dropper entrance serves to increase surface tension and viscous drag forces at the inlet and also prevents dirt entering the dropper body. Water flows through a narrow reentrant channel reaching the dropper outlet tube. The effect of these changes is to increase the natural frequency of oscillation of the water column while introducing some damping to minimize the oscillation amplitude and reduce the effect of impulsive inputs. Thus significant column oscillation effects are only expected at high drop rates when the increased number of drops counted during a sample period will offset the errors.

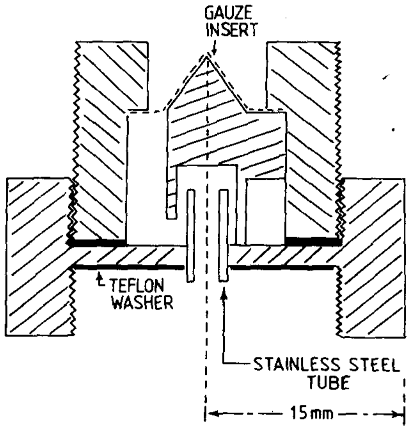

FIG. 3. Cross section of the improved dropper raingage unit.

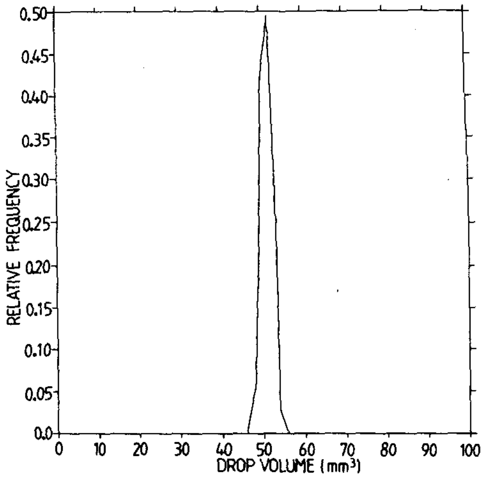

FIG. 5. The drop volume distribution for the improved gage unit under constant input flow rate conditions. The mean drop rate was approximately 1 Hz.

Detection of drops is by means of a two-wire probe. Drops falling through this probe cause a temporary electrical connection across the gap between the two wires. Some care is required in adjusting the wire gap to prevent the development of a permanent water bridge. The resistivity of rainwater in the Auckland region is of the order of 0.2 MΩ cm, sufficiently high to require the use of high impedance circuitry following the probe. A CMOS Schmitt trigger device (74C93) is used to provide output pulses from the detector.

4. Calibration and laboratory performance

Calibration of the gage makes use of the disdrometer. Figure 4 shows a plot of flow rate versus drop rate for a dropper under conditions of variable flow rate. Points on the plot were produced from 10-s averages of the flow rate estimated by summing the drop volumes measured by the disdrometer. Unlike the N–W gage, these data show excellent linearity over the entire flow rate range; this difference is particularly noticeable when the drop rate is low. The new dropper performs well up to a drop rate of approximately 15 Hz. At higher drop rates the drop production becomes erratic and eventually a jet of water is produced rather than a drop stream.

A linear least-squares fit of the calibration data to $F = kD$ where F is the flow rate ($\mathrm{mm^3\ s^{-1}}$) and D is the drop rate (Hz) gives $k = 57.2$ with a correlation coefficient of 0.998. Calibration of eight similar gages assembled for the present work showed a variation in k from one gage to another, with the range of variation being of the order of 15%.

Figure 5 shows the drop volume distribution for a steady drop rate of ~1 Hz for the same gage used above. This distribution is to be compared with Fig. 2 for the original N–W design. Owing to the 5% random

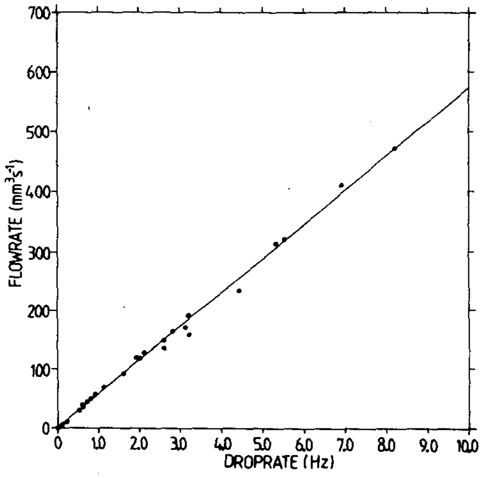

FIG. 4. A typical calibration for the improved gage demonstrating its linearity.

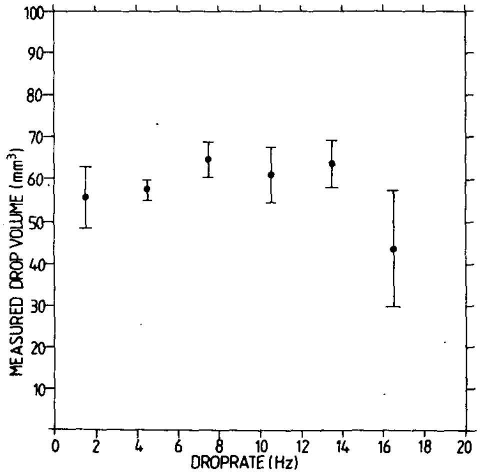

FIG. 6. Drop volume as a function of drop rate for the improved gage unit; bars correspond to standard deviations of drop volumes.

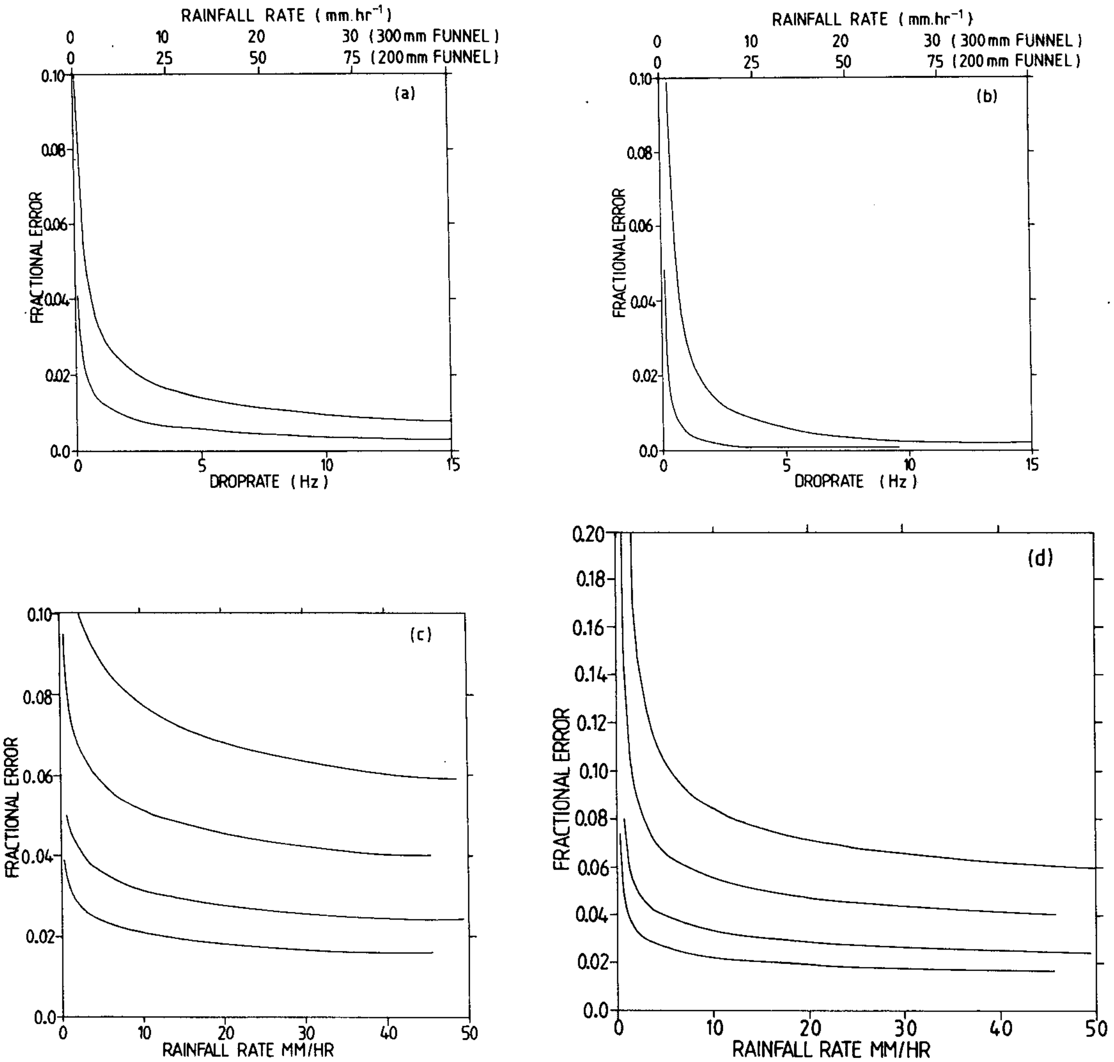

FIG. 7. Raingage errors. (a) Fractional error due to drop volume variation as a function of drop rate for 10-s (upper) and 60-s (lower) sample periods; (b) quantization error under the same conditions as (a) for 10-s (upper) and 60-s (lower) sample periods; (c) statistical sampling error as a function of rainfall intensity *I* for the following cases (top to bottom): 200-mm diameter funnel with 10-s sample period; 300-mm funnel with 10-s sample period; 200-mm funnel with 60-s sample period; 300-mm funnel with 60-s sample period; (d) total gage error with curves as for (c) above.

error in the measurement of drop volume by the disdrometer, the true variation in drop volume is rather less.

Figure 6 shows a typical example of the variation of drop volume with flow rate. The fractional error (ie, the standard deviation/mean) in drop volume is independent of drop rate up to ~15 Hz and is of the order of 10%; it follows that as the drop rate or sample period is increased, the fractional error in rainfall amount recorded due to drop volume variation will decrease due to the increased drop counts measured (see Fig. 7a).

Another major source of error is the quantization error. During any sample period the drop count will be in error by up to ±0.5 drops. The density function for this type of error is rectangular, and hence the standard deviation of the drop count is 0.29 drops. Figure 7b shows that the fractional error in recorded rainfall due to quantization decreases rapidly with both increased drop rate and increased sample period.

In order to cover the large dynamic range of rainfall rates of interest, funnels of 200 and 300 mm diameter were chosen. Estimates of the variations of the above errors as a function of rainfall rate for each funnel size are displayed using the appropriate abscissae in Figs. 7a and 7b.

In the field, statistical sampling errors resulting from the discrete nature of rainfall also contribute to the uncertainty in measuring rainfall rates. These errors are a function of rainfall rate, funnel size, and sample period. Figure 7c shows the fractional standard devia-

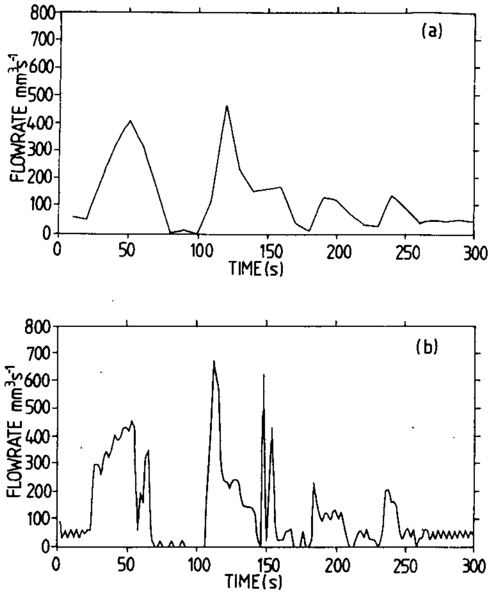

FIG. 8. The time response of the improved raingage unit: (a) using 10-s averages; (b) using 2-s averages.

tion in I due to this source of error as a function of I for both funnel sizes used and for two sample periods, estimated using the treatment of Gertzman and Atlas (1977). This sampling error decreases less rapidly with rainfall rate than either of the other error components and dominates above $\sim I = 5$ mm h^{-1}. The errors are combined in Fig. 7d, which shows that the total fractional error in the measurement of I using the improved gage is predominantly due to uncertainties caused by the discrete nature of rainfall.

The time response of the gage to rapid variations in the input flow can be estimated from Figs. 8a and 8b; these show drop rates corresponding to a rapidly and randomly changing input flow rate averaged over 10 and 2 s, respectively. A comparison of the fine structure visible in the figures shows that the gage has a response time shorter than the 10-s resolution desired and probably in the region 2–5 s. In use, the response time is increased due to the response of the attached funnel, which varies both with rainfall rate and wetness of the funnel surface (Mellanby, 1976).

For an additional check the number of drops is counted using the drop detector and the discharged water is collected; this allows an average drop volume to be determined. For all gages, results of the two calibration methods have been found to agree to within experimental error, typically 1%–2%. Drift of the calibration has also been investigated over a period of several months. Variations of k from the original calibrations are less than 5%.

5. Field performance

Field evaluation of the gage was performed both by comparing the gage performance with that of a standard natural-siphon raingage and also by intercomparison of measurements made by several gages of the improved design.

During the initial field trials it was found that occasionally water collecting on the underside of the dropper, through condensation and splashing, formed a water bridge to the dropper tip, causing either oversized drops to be produced or water to drain across the water bridge to the edge of the dropper body. In either case an underestimation of the rainfall rate results. This condition has been eliminated by the application of a uniform layer of Teflon spray on the underside of the dropper body, excluding the dropper tip.

Figure 9 shows a comparison of the cumulative rainfall measured under showery conditions by the improved gage with that measured by a natural siphon raingage (Lambrecht model 1507) situated in Albert Park, Auckland and operated by the New Zealand Meteorological Service. The data points are successive 60-s estimates of the cumulative rainfall, the natural siphon data being digitized from a 24-h chart record. The agreement between the two gages is excellent if the errors involved with digitizing the Lambrecht record are considered, the correlation coefficient being 0.999. The long-term trend is for the improved raingage to underestimate the cumulative rainfall slightly in comparison to the Lambrecht gage, although the difference of about 5% is within the combined calibration error of the two gages. The differences shown in the initial part of the record are due to inaccuracy in the time measured from the Lambrecht chart record and are of no consequence.

Figure 10a, b shows measurements made by two of the improved gages at the same location; the sample period here is 10 s. The degree of correlation between the two records is very good, as may be seen from Fig. 10c, the correlation coefficient being 0.994. Differences between the two records are consistent with the errors discussed in section 4 and with differences in the funnel response between the two gages.

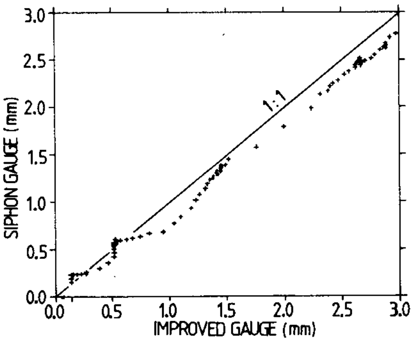

FIG. 9. A comparison of the improved raingage with a standard natural siphon gage. The scatter plot shows the cumulative rainfall at successive intervals of 60 s; the correlation coefficient is 0.999. The solid line represents the ideal situation where both gages have the same response.

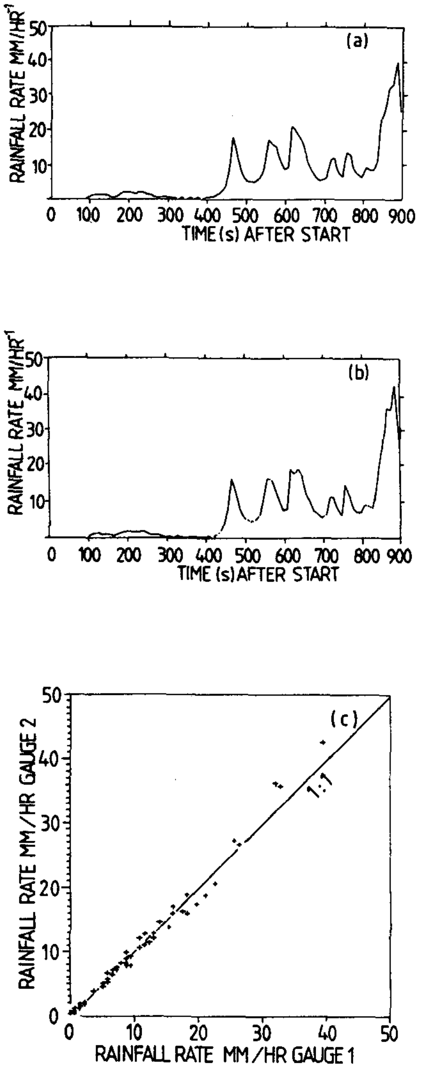

FIG. 10. Simultaneous records obtained using two improved gages installed at the same location: (a) 200-mm funnel; (b) 300-mm funnel; (c) a comparison of the rainfall rates of (a) and (b) showing a correlation coefficient of 0.994; the solid line represents the ideal situation where both gages have the same response. The sample period used was 10 s.

6. Conclusion

Evaluation of the rapid-response raingage described by Norbury and White (1971) has disclosed a serious design defect. Resonant oscillation of the water column causes unstable drop production at low drop rates (1–2 Hz) with drops being produced in clusters rather than as a uniform stream. Examination of the causes of the oscillation has led to an improved gage design that eliminates the problem. The new gage produces drops at a rate linearly proportional to the rainfall rate so that it is useful not only for short (~10 s) sample intervals but also for providing cumulative rainfall information over longer intervals.

An examination of sources of error shows that statistical sampling errors due to the discrete nature of rainfall are dominant and instrumentation errors are usually negligible. The quantization error for a gage of the design presented here is at least an order of magnitude lower than that of a tipping bucket raingage. The time response of the dropper unit to rapid variations of input flowrate is shorter than the expected rise-time of the funnels used in the gages. Data obtained from the gage in the field have shown good correlation with data obtained from a standard natural siphon gage. Measurements made by similar gages at the same location also show good agreement; differences are consistent with the estimated instrument error.

A number of gages of the improved design are currently in operational use; seven form a linear array as part of a field system for the investigation of fine-scale variations in rainfall (Hosking and Stow, 1985), while a further 15 are arranged in a grid spanning the Waitakere ranges to the West of Auckland in a study of orographic influences on rainfall in the region (Gray, 1985).

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