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CALIBRATION OF THE TIPPING-BUCKET RAINGAGE

by

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As per Guide for Authors, all words that should be in italics have been underscored.

MANAGEMENT PERSPECTIVE

Hydrologic and hydraulic studies sometimes require accurate measurements of the rate at which rain is falling.

Rainfall intensities as measured by a "tipping bucket" raingage may have errors. This report has investigated the source of errors and also provides a calibration curve to correct the measured intensity to the actual intensity. Notable is the observation that the performance of the gage is clearly affected by the surface tension of the water and the condition of the bucket surfaces. The results have implications for raingage design and maintenance. Historical data may also require correction.

T. M. Dick, Chief
Hydraulics Division
October 1, 1980

VUES DE LA DIRECTION

Les études hydrologiques et hydrauliques demandent parfois des mesures exactes de l'intensité de la pluie.

Les intensités de pluie mesurées par un "auget basculeur" peuvent présenter des erreurs. Le présent rapport étudie les sources d'erreurs et donne une courbe d'étalonnage permettant de ramener l'intensité mesurée à l'intensité réelle. Il est intéressant de noter que le rendement du pluviomètre est nettement tributaire de la tension en surface de l'eau et de l'état de la surface des augets. Les résultats de l'étude touchent donc la conception et l'entretien du pluviomètre. Peut-être faut-il aussi rectifier les données chronologiques.

T. M. Dick, chef
Division de l'hydraulique
le 1er octobre 1980

CALIBRATION OF THE TIPPING-BUCKET RAINGAGE

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ABSTRACT

Three models of the tipping-bucket raingage were calibrated in the laboratory by adjusting the volume required to tip the bucket and by correcting the raingage output readings. In the volumetric calibration, the effects of raingage installation, the wetting of buckets, and the surface tension of the liquid used were considered. To calibrate the raingage output, the recorded rainfall intensities (i.e. calculated from the raingage record) were compared to the actual intensities calculated from the rate of inflow to the raingage receiver. Recorded intensities were typically smaller than actual ones, in extreme cases by as much as 10 percent. An explanation for this underestimation was found by considering the loss of water during the bucket rotation. Estimates of these losses were obtained by timing the bucket movement for various rainfall intensities. Finally, the sensitivity of the tipping-bucket raingage output to the variations in the basic design parameters of the raingage was studied numerically using the analytical expression derived for the recorded intensity.

ÉTALONNAGE DU PLUVIOMÈTRE ENREGISTREUR À AUGETS BASCULEURS

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RÉSUMÉ

En laboratoire, on a étalonné trois modèles de pluviomètres à augets basculeurs en établissant le volume d'eau nécessaire pour faire basculer l'auget et en corrigeant les résultats indiqués par le pluviomètre. Dans l'étalonnage du volume, on a tenu compte des répercussions de l'installation du pluviomètre, du mouillage des augets et de la tension en surface du liquide. Pour étalonner la quantité fournie par le pluviomètre, on a comparé l'intensité de la pluie enregistrée (calculée à partir du relevé du pluviomètre) à l'intensité réelle calculée à partir de la vitesse d'arrivée de l'eau dans le réceptacle du pluviomètre. Comme d'ordinaire, les intensités enregistrées se sont révélées inférieures aux intensités réelles, d'où un écart atteignant 10% dans les cas extrêmes. On a expliqué cette sous-estimation par la perte d'eau survenant pendant la rotation de l'auget. On a évalué cette déperdition en minutant le mouvement de l'auget pour diverses intensités de pluie. En dernier lieu, on a étudié numériquement la sensibilité des indications du pluviomètre à augets basculeurs aux variations des paramètres fondamentaux de conception du pluviomètre, en utilisant l'expression analytique dérivée pour l'intensité enregistrée.

INTRODUCTION

The invention of the tipping-bucket raingage dates back to the 18th century when Sir Wren and Robert Hook proposed a raingage with a single-compartment tipping bucket and mechanical balancing (Biswas, 1970). Over the years, the original invention has been further refined and the tipping-bucket raingage has become one of the most popular recording raingages used by many national weather service agencies.

Advantages of the tipping-bucket raingage include high accuracy of recording low-to-intermediate intensity rainfalls, a superior mechanism for actuating circuits, suitability for remote recording, and reliability (Linsley, 1973; Smoot, 1971). On the other hand, the tipping-bucket raingage is known to underestimate the rainfall at higher intensities because of the rainwater "lost" during the movement of the bucket (Bruce, 1966). This shortcoming can be remedied by calibrating the raingage (Smooth, 1971).

A literature survey has not yielded much information on the magnitude of underestimation of the rainfall recorded by the tipping-bucket raingage (WMO, 1973). In one case, the duration of the tipping-bucket movement was estimated as a few milliseconds (Texas Electronics, no date). The corresponding underestimation of rainfall at extreme intensities would be about 0.1 percent.

To provide some data on the accuracy of the tipping-bucket raingages, three different gage models were tested in the laboratory. The results of these tests are discussed in the following.

DESCRIPTION OF THE TIPPING-BUCKET RAINGAGE

Principle of Operation

The tipping-bucket raingage consists of a receiver, the tipping-bucket assembly with circuitry for generating an output signal and a recorder. The receiver is a funnel collecting rainwater (see Fig. 1). The diameter of the receiver typically varies from 0.203 m to 0.305 m. The funnel drains into a bucket which is a half of a two bucket receptacle pivoted on a knife edge. As the upper bucket fills to a specified amount, the balance will tip, the lower bucket is brought into position under the spout and the filled bucket is emptied. Each tip of the bucket generates an electric impulse by means of such devices as a magnetic reed switch or a mercury tilt switch. This impulse is then transmitted to a recorder.

The tipping-bucket raingage is equipped with two calibration stop screws (one for each bucket compartment) which are used to set the tipping of the bucket after a preselected amount of rain was collected by the receiver. Such a calibration is referred to here as the volumetric calibration of the tipping-bucket and is described in one of the following sections.

Tipping-Bucket Raingages Tested

In the study described here, three different makes of the tipping-bucket raingage were tested. In particular, the instruments studied included the (Canadian) Atmospheric Environment Service (AES) Tipping-Bucket Raingage, the Stevens Tilting Bucket Rainfall Recording Accessory manufactured by Leupold and Stevens (LS), Inc. and Model 6118-1 Tipping-Bucket Raingage

manufactured by Texas Electronics (TE), Inc. Although the selection of makes was given by their availability from previous studies, the instruments tested represent a fair range of models available on the market. Basic characteristics of the raingages tested are given in Table I.

VOLUMETRIC CALIBRATION OF THE TIPPING BUCKET

The calibration of the tipping-bucket volume is done in the laboratory using a pipette to measure the volume of water required, for each compartment, to tip the balance. By adjusting the calibration stop screws, this volume is typically set to correspond to the nominal bucket volume $V_n = A h_n$, where A is the area of the receiver and h_n is the nominal rainfall depth increment. As discussed later, the bucket volume is sometimes adjusted to a volume smaller than the nominal value, in order to compensate for rainfall underestimation at higher intensities.

Since the bucket volumes observed during the laboratory calibration varied, at least 20 readings were taken for each setting of the calibration screws. The standard deviation of these readings about the mean was, for all three gages, less than 2 percent of the mean. Such random variations resulted from variations in the force required to set the tipping bucket in motion. The volumetric calibration was continued until the bucket volume was within 2 percent of the nominal value. The remaining deviation was then accounted for by correcting the nominal bucket volume and the corresponding nominal rainfall depth increment.

Apart from random variations in the measured bucket volumes, some systematic variations in the bucket volumes were also observed. These systematic changes were caused by installation of the raingage out of level, the wetting of the bucket compartments and the liquid used in the calibration.

The raingage to be calibrated must be properly levelled. Deviations of several degrees from the level affected the balancing of the bucket and changed the volumes required to tip the bucket by several percent.

The wetting of bucket compartments had a definite effect on the calibrated volumes. As shown in Table II for the AES raingage, the calibration volumes for the wetted bucket were, on the average, about 5 percent higher than those observed for the dry bucket. This difference was statistically significant at the 95 percent level of confidence and could be explained by an incomplete drainage of the emptied compartments. The amount of water remaining in the emptied compartment varied from 0.15 mL, for the LS and TE raingages, to 0.3-0.5 mL for the AES gage.

To fill the upper compartment, less water is needed because of the residue present. However, the turning moment (resisting the bucket rotation) of the residue in the lower compartment has to be overcome by adding some more water to the upper comaprtment. Since the residue in the lower compartment is often concentrated close to the outflow lip where the moment arm is the largest, the extra volume needed to tip the balance may substantially exceed the residue volume.

It was observed that the magnitude of residue in the bucket was affected by the slope of the bucket bottom in a resting position and by the geometry of the outflow lip. The largest residues were observed for the AES gage which had the smallest slope of the bucket bottom and the outflow lip extending over the full bucket width. The other two gages had smaller residues and this was achieved by using a pointed outflow lip slightly bent downwards to reduce the amount of water attached to the lip after drainage. Consequently, although for the LS and TE gages the bucket volumes observed for the wet bucket still exceeded those observed for dry buckets, the differences were not statistically significant.

Since raingages in the field operate with wetted bucket compartments, except for the first tip, the volumetric calibrations obtained for wetted compartments were adopted for further work.

Finally, it was also observed that different results were obtained for two liquids used in volumetric calibrations - the rainwater and tap water (see Table II). The tap water produced slightly higher calibrated bucket volumes than the rainwater. This was caused by different surface tensions of two liquids. The tap water had a lower surface tension and produced higher residuals and therefore higher bucket volumes than the rainwater.

Apart from the surface tension of the metered liquid, the wettability of the bucket inside surface also affects drainage residues and the volumetric calibration. To demonstrate this effect, the tipping bucket of the AES gage was waxed inside. This resulted in smaller residues and a 4 percent reduction in volumes required to tip the balance (see Table II). A practical implication following from this experiment is the fact that the volumetric calibration can change, without adjustment of calibration screws, by variation of the bucket wettability through surface oxidation or contamination by impurities.

The volumetrically calibrated raingages were ready for the calibration of their output described in the following section.

CALIBRATION OF THE TIPPING-BUCKET RAINGAGE OUTPUT

In the calibration of the tipping-bucket raingage output, rainfall intensities calculated from the raingage record are compared to the actual intensities calculated from the rate of inflow to the raingage receiver. A description of analytical considerations and calibration procedures follows.

Analytical Considerations

It is generally acknowledged that the intensities calculated from the tipping-bucket movement (referred to here as recorded intensities) underestimate the actual intensities, because of water lost during the bucket movement (Bruce, 1966; WMO, 1973). An analytical expression for the relationship between the recorded and actual intensity is derived below.

The recorded intensity can be expressed as

$$i_r = h_n/t_t \tag{1}$$

where h_n is the nominal rainfall depth increment per one tip, and t_t is the time lapsed between two consecutive tips.

The time t_t can be expressed as

$$t_t = t_n + \Delta t \tag{2}$$

where t_n is the time required to fill the bucket compartment and Δt is the time lapsed from the start of the bucket movement to the point in time when the compartment being emptied does not receive any more water from the receiver.

The duration of the bucket compartment filling, t_n, can be further expressed as

$$t_n = \frac{V_n}{Q_a} = \frac{h_n}{i_a} \tag{3}$$

where V_n is the nominal compartment volume required to tip the balance, Q_a is the rate of inflow to the raingage receiver, and i_a is the actual intensity defined

as the mean velocity of the flow of rainwater through the receiver area. Although the flow of rainwater through the receiver orifice is discontinuous, by the time the rainwater reaches the receiver spout, the flow area has been reduced so much that the flow through the spout out into the bucket may be considered to be continuous for intensities higher than about 50 mm/hr. Thus the analysis given here is applicable to rainfall intensities higher than the aforementioned limit.

After substituting eqs. (2) and (3) into eq. (1) and some rearranging, one obtains the following expression

$$\frac{i_r}{i_a} = \frac{h_n}{h_n + \Delta t\, i_a} \qquad\qquad (4)$$

A brief examination of eq. (4) indicates that the recorded and actual intensities are identical only for the case of $\Delta t = 0$ (disregarding the trivial case of $i_r = i_a = 0$). For all the other cases (i.e. $\Delta t > 0$), the recorded intensity is smaller than the actual one. This deviation will increase with an increasing Δt and a decreasing h_n. In other words, the slower the bucket movement and smaller the bucket size, the larger the underestimation of actual intensity by the recorded intensity.

Eq. (4) was used to investigate the sensitivity of the ratio i_r/i_a to the variation in the raingage parameters h_n and Δt. The results of these numerical experiments are shown in Fig. 2. For extreme cases of slow bucket movement ($\Delta t = 0.75$ s), small nominal depth ($h_n = 0.1$ mm) and extreme actual intensities, the simulated recorded intensities amounted to 70 percent - 80 percent of the actual intensities.

In another approach to the calibration of the tipping-bucket raingage output, the rainfall depth increment at which the bucket tips is set at a smaller

than nominal value. The filling of the bucket compartments then takes less water and, consequently, the losses during the bucket movement are partially compensated for. In this case, the time lapsed between two tips, t_t, can be expressed as

$$t_n = t_f + \Delta t \tag{5}$$

where t_f, the duration of the bucket filling, can be expressed as

$$t_f = \frac{V_n - \Delta V}{Q} = \frac{h_n - \Delta h}{i_a} \tag{6}$$

where ΔV and Δh are the reductions in the nominal compartment volume and in the corresponding rainfall depth increment, respectively.

After substituting eqs. (5) and (6) into eq. (1), one obtains

$$\frac{i_r}{i_a} = \frac{h_n}{h_n - \Delta h + \Delta t \, i_a} \tag{7}$$

It follows from eq. (7) that, for $\Delta h = \Delta t \, i_a$, $i_r = i_a$. It is therefore possible to select a reference intensity and the corresponding value of Δh for which the recorded intensity will equal the actual intensity. For actual intensities smaller than the reference value, the recorded intensities would exceed the actual ones, but by lesser amount than in the case where the bucket volume is set to correspond to the nominal rainfall depth increment.

Eq. (4) served for the planning of calibration experiments described in the following section.

Calibration Procedures

In the laboratory arrangement, inflows to the receiver varying from .07 mL/s to 6 mL/s were provided by means of a constant-head siphon equipped with a control valve. The corresponding actual intensities varied from 6 mm/hr to 400 mm/hr. It should be stressed that the extreme intensities employed were more of a theoretical than practical interest.

The outflow from the siphon was distributed inside the raingage receiver. Water draining from the tipping bucket was collected in glass beakers and weighted on a laboratory weigh scale with the readout to the nearest 0.01 g. The tips of the tipping bucket were recorded by a recorder and timed using a stop watch. In special experiments, the movement of the tipping bucket was timed using time-lapse photography.

In individual calibration runs, a preselected siphon discharge was first established and introduced into the raingage receiver over a time period required to tip the bucket from 40 to 100 times. The actual intensity was determined from the weight of water collected during the run. The recorded intensity was calculated from the recorded number of tips and the time lapsed.

Results

The calibration curves for the three tipping-bucket raingages tested are shown in Fig. 3. These curves could be used to correct the intensities recorded by the tested raingages. For all three raingages, a significant difference between the recorded and actual intensities was apparent. At low intensities, say less than 25 mm/hr, the recorded intensity may exceed the actual intensity. In other words, the tipping bucket may tip at slightly lower volumes than those

established through the volumetric calibration. From the practical point of view, the differences between low recorded and actual intensities are of little interest, particularly if one considers the low absolute numbers involved. In fact, the largest difference between low recorded and actual intensities (say i≤25 mm/hr) plotted in Fig. 3 is less than 0.14 mm/hr which is indeed a negligible value.

For intensities higher than 25 mm/hr, the recorded intensity is always smaller than the actual one. The difference between two intensities grew larger with increasing intensities and could exceed 10 percent for extreme intensities (i > 200 mm/hr).

The calibration curves for all three raingages were quite similar. The LS raingage yielded slightly smaller differences between the recorded and actual intensity.

Another objective of the present study was to verify eq. (4) which describes the relationship between the recorded and actual intensities. For that purpose, the duration of the bucket movement, Δt, was also measured, over a wide range of intensities, for all three raingages. The results of these measurements are given in Fig. 4.

It can be inferred from Fig. 4 that the duration of the bucket movement, from a resting position to the central position, varies from 0.3 s to 0.6 s for various intensities and the raingages tested. Such values contradict the estimates of Δt reported elsewhere as a few milliseconds (Texas Electronics, no date).

The LS raingage had the fastest movement which also explains why this raingage yielded the smallest differences between the recorded and actual intensities. The relatively fast movement of the LS tipping bucket may follow from a relatively low mass of the bucket and the resulting faster acceleration of

the bucket rotation in the initial stage of movement. The other two raingages had comparable durations of the bucket movement.

Examination of data in Fig. 4 indicates that Δt depends, to some extent, on the actual intensity. The higher the intensity, the shorter the duration Δt. This follows from the fact that, for higher intensities, the inflow to and the overfilling of the upper compartment are larger, thus producing a larger force which causes the bucket to rotate faster.

The relationship between observed Δt's and i_a's was described, for individual gages, by regression equations which were plotted in Fig. 4.

Experimental calibration curves were compared to those calculated from Eq. (4) using Δt's estimated, by means of regression analysis, for individual raingages. The results of these comparisons are presented in Fig. 5.

On the average, the calibration curves calculated from eq. (4) differed from the smoothed experimental calibration curves by less than 2 percent. It can be concluded that the differences between the recorded and actual intensities can be explained, to a large extent, by considering the duration of the bucket movement as done in eq. (4).

The comparisons of calculated and experimental calibration curves were adversely affected by appreciable uncertainties in observed Δt's. These uncertainties follow from a very slow start of the bucket rotation. Once the bucket is set in motion, the rotational velocity increases rapidly as the weight of water in the bucket and the arm along which this weight acts increase. Other sources of discrepancies between the calculated and experimental calibration curves include incomplete drainage of bucket compartments and the bucket tipping at lower than nominal volumes for low intensities.

Observed Δt's can be used to derive approximate general rating curves for raingages similar to those investigated in this study. For that purpose, all data in

Fig. 4 were grouped together and approximated by a single linear relationship which was then used in conjunction with eq. (4) to produce rating curves for various rainfall depth increments h_n. These rating curves are given in Fig. 6.

Finally, the observed Δt's can be used in conjunction with eq. (7) to estimate the approximate reductions in the rainfall depth increment, Δh, required to match the recorded and actual intensities at any reference point. The values of Δh were calculated for the AES raingage and plotted in Fig. 7. For example, to match the recorded and actual intensity at 50 mm/hr, the depth increment h_n and the corresponding bucket volume V_n at which the balance tips would have to be reduced by about 3 percent.

CONCLUSIONS

Investigations of three different tipping-bucket raingages indicate that these instruments, if volumetrically calibrated, may underestimate extreme actual intensities by about 10 percent. Without the volumetric calibration, additional errors may be introduced.

The volumetric calibration is affected by the raingage installation out of level, the wetting of the bucket compartments, and the wettability of the compartment surface which also depends on the surface tension of the calibration liquid. Each of the above factors may change the calibrated bucket volume by several percent.

The differences between the recorded intensities (derived from the raingage record) and the actual intensities can be explained by considering the duration of the bucket movement and the water losses taking place during this period. The movement of the bucket from a resting position to the central position takes about 0.3 s-0.6 s. The shorter times correspond to higher intensities and vice versa.

The recorded intensity can be expressed as a function of the actual intensity, the rainfall depth increment, and the duration of the bucket movement. The underestimation of the actual intensities by the recorded intensities increased with a decreasing rainfall depth increment, increasing duration of the bucket movement, and increasing actual intensity. The analytical expression derived for recorded intensities was verified by the experimental data.

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TABLE I   Basic characteristics of the raingages tested

Raingage Make	Canadian Atmospheric Service (AES)	Leupold and Stevens (LS)	Texas Electronics (TE)
Nominal rainfall depth increment (mm)	.254[1]	.254	.254
Receiver diameter (m)	.254	.203	.259
Receiver area (m^2)	.05067	.03237	.05269
Approximate bucket dimensions (total length x width) (m)	.140x.025	.106x.016	.149x.039
Nominal bucket volume (cm^3)	12.9	8.2	13.4
Angle of bucket rotation from one resting position to another (degrees)	49°	68°	59°

[1] Recent models are adjusted to 0.2 mm.

TABLE II   Results of volumetric calibrations for various conditions

Experimental Run	A	B	C	D
Calibration liquid	rainwater	rainwater	tap water	tap water
Surface tension at 18.5°C (dynes/cm)	71.5	71.5	64.0	64.0
Wetting of the bucket	wet	dry	wet	wet
Treatment of the bucket inside surface	none	none	none	waxed
Mean bucket volume (cm^3)	13.05	12.32	13.19	12.68
Standard deviation about the mean (cm^3)	.22	.10	.24	.43

Confidence limits (95 percent level of

significance)

         A - B   .617-.820

         C - A   .021 - .272

         C - D   .307 - .766

RECEIVER SPOUT

Q

CALIBRATION
STOP SCREWS
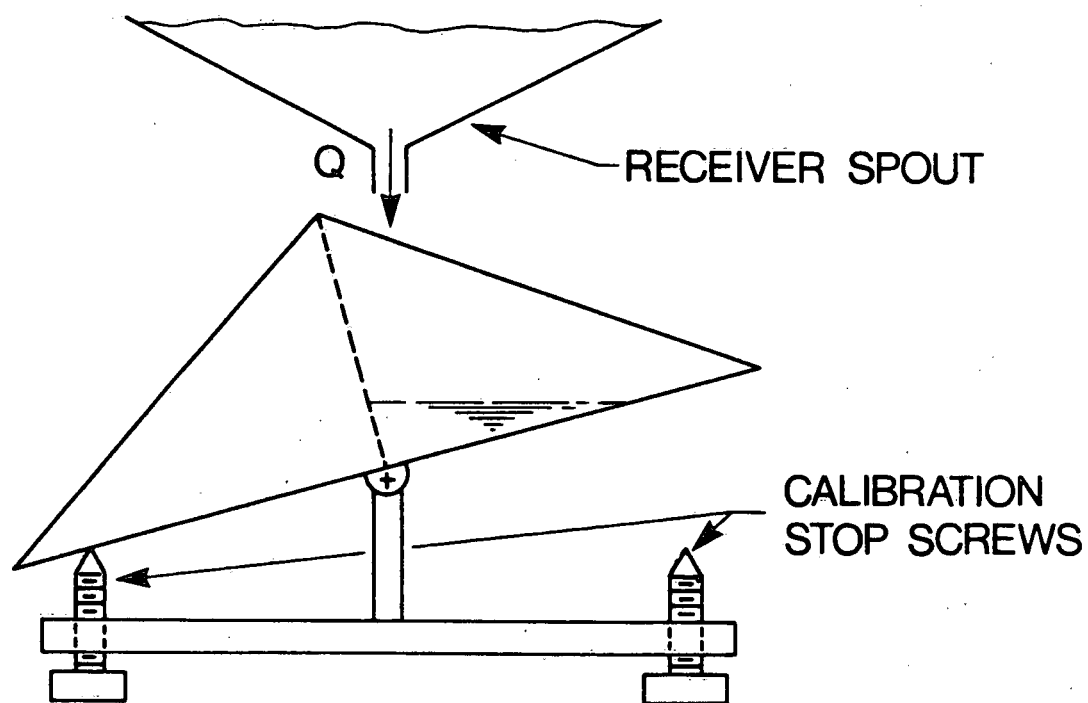
Figure 1   Tipping-Bucket Assembly
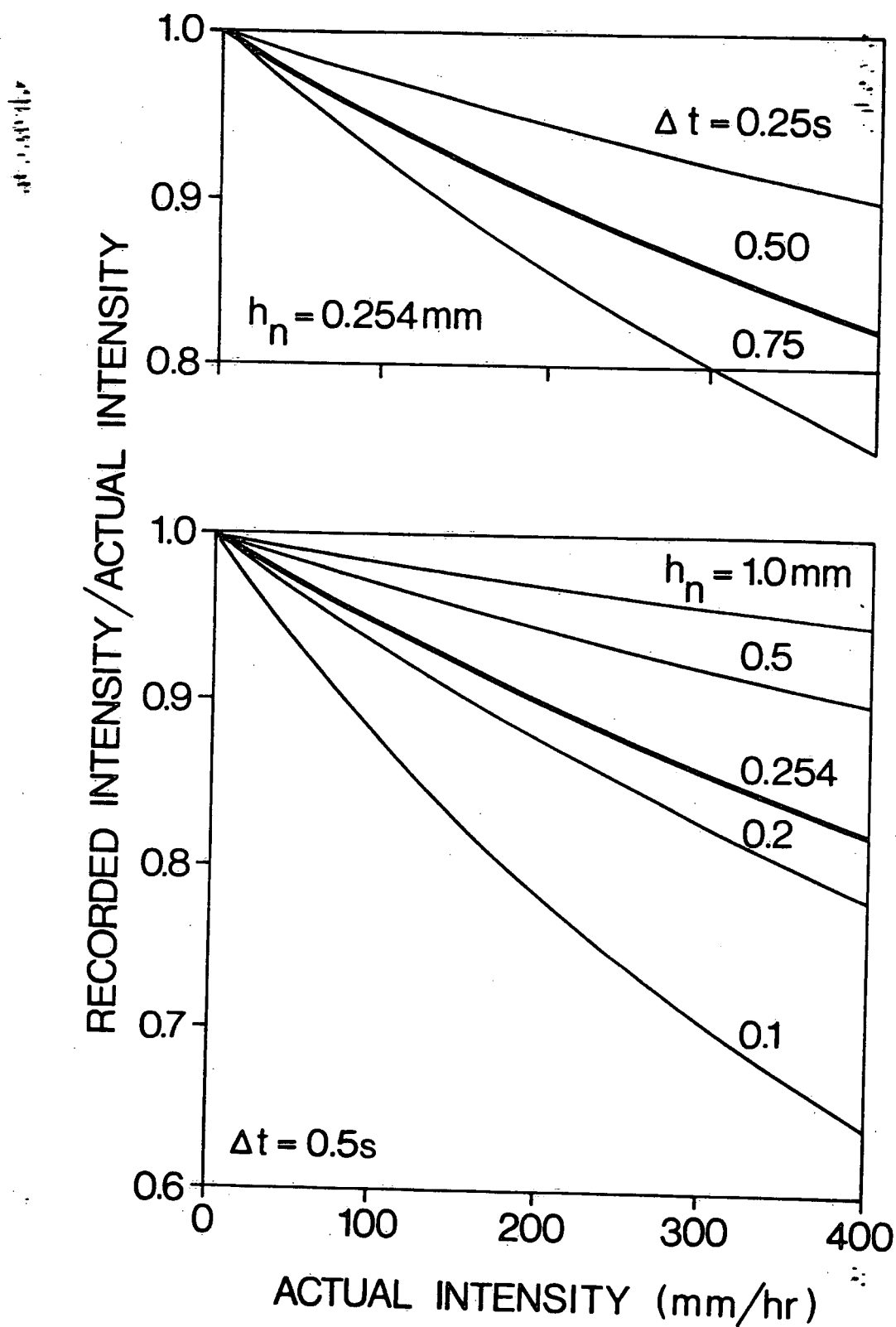
Figure 2   Sensitivity of the i_n/i_a Ratio to Variations in Selected Raingage Parameters
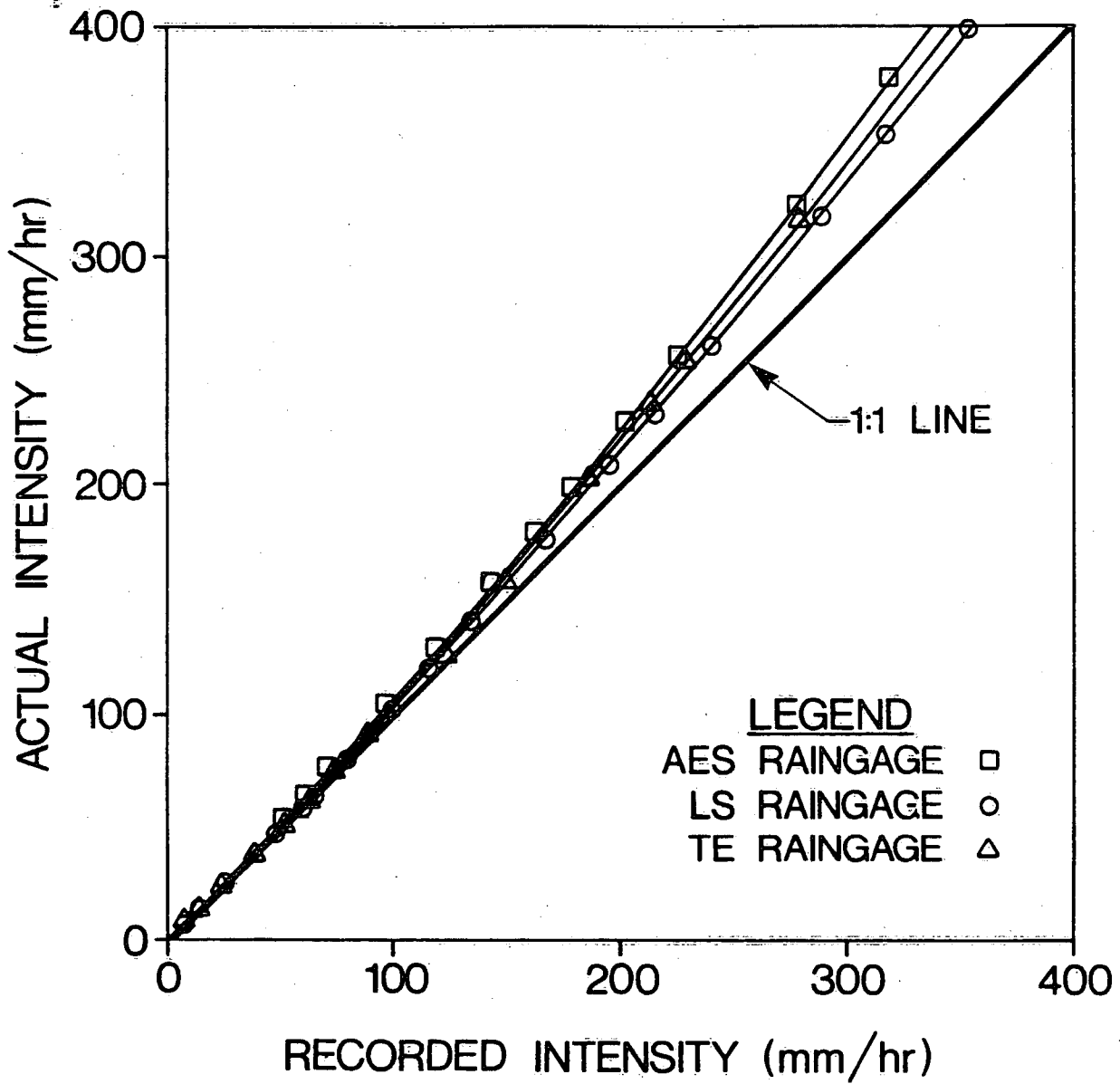
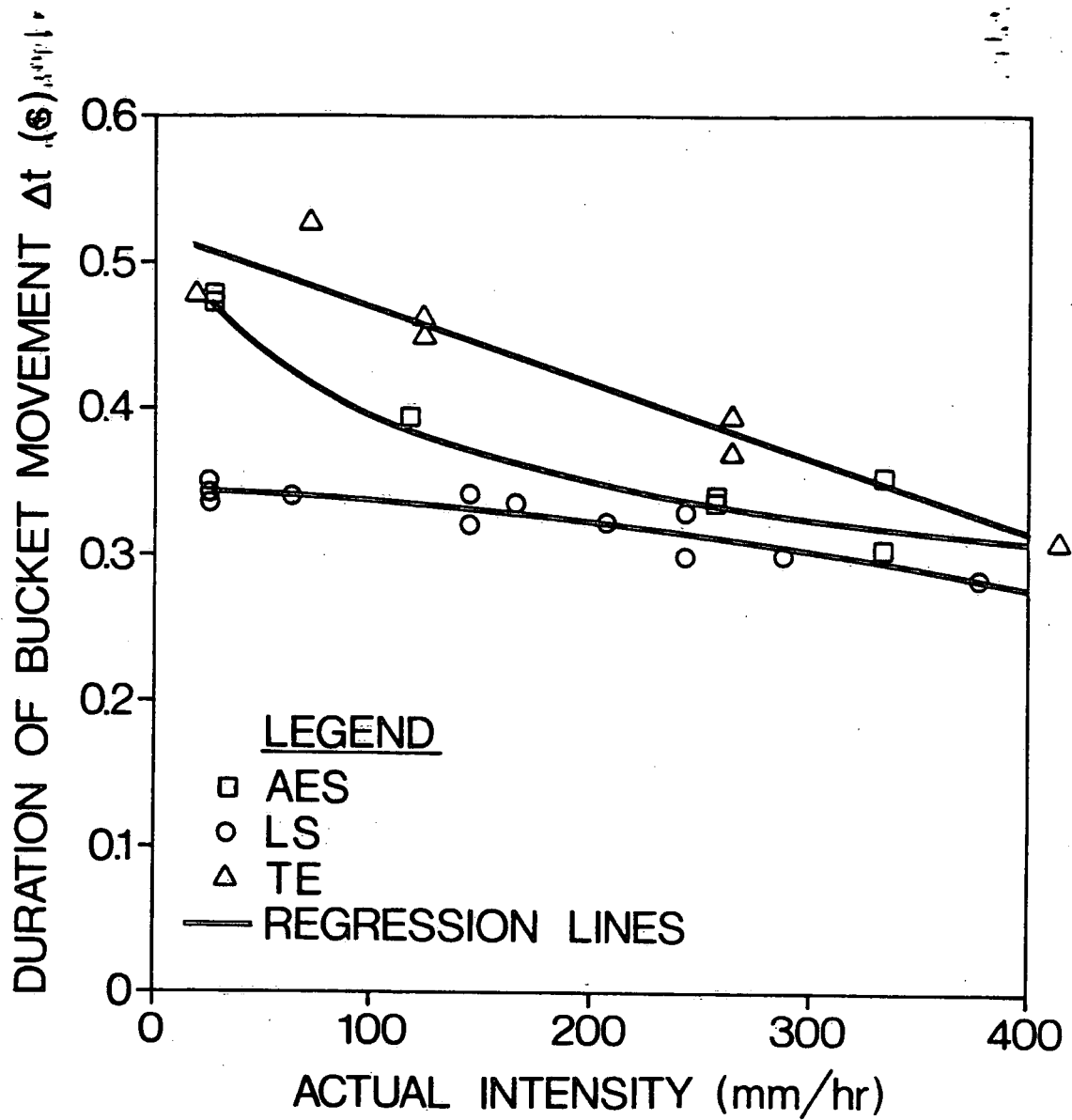Figure 3   Calibration Curves of the Raingages Tested
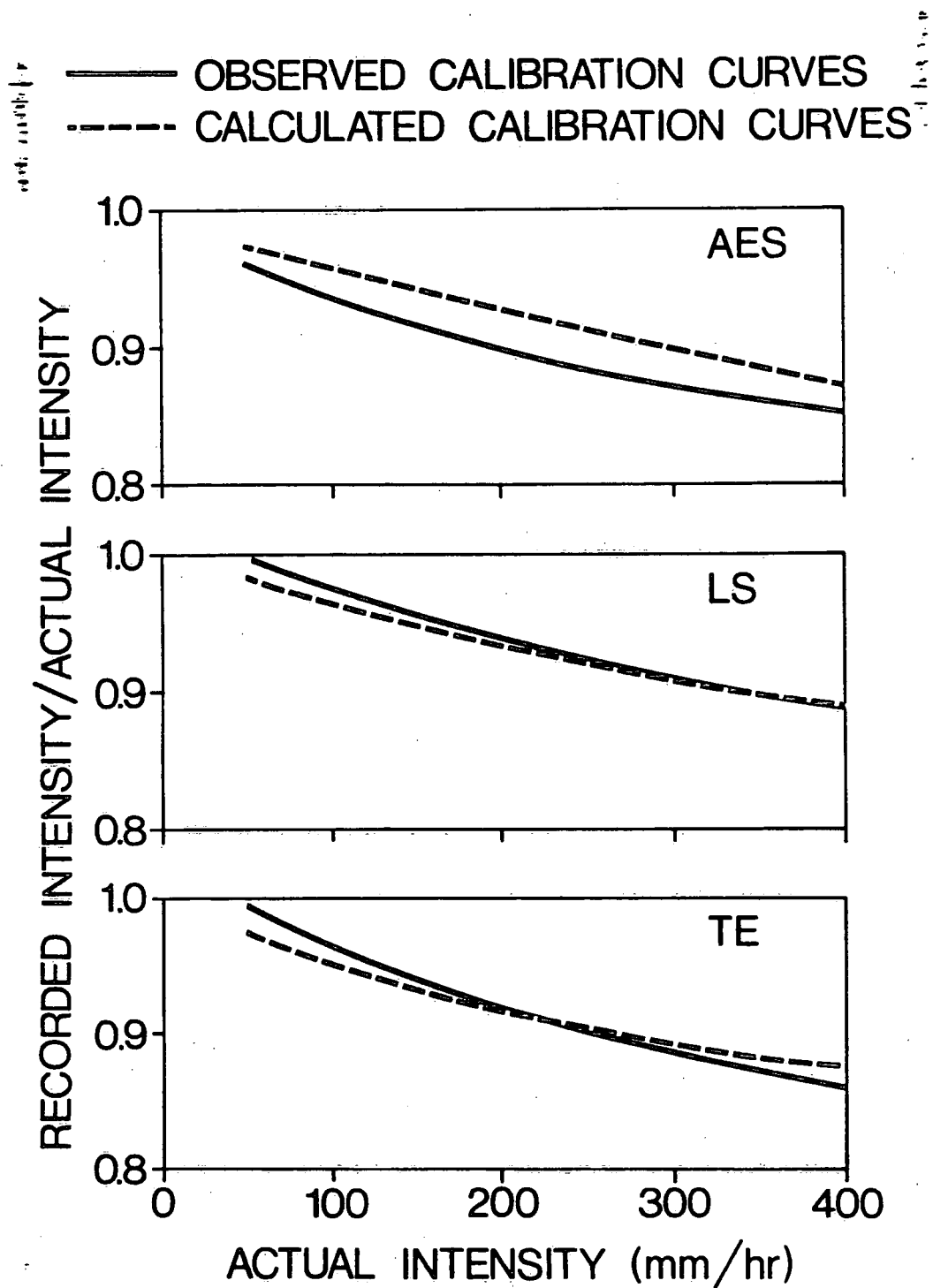
Figure 4   Durations of the Tipping-Bucket Movement

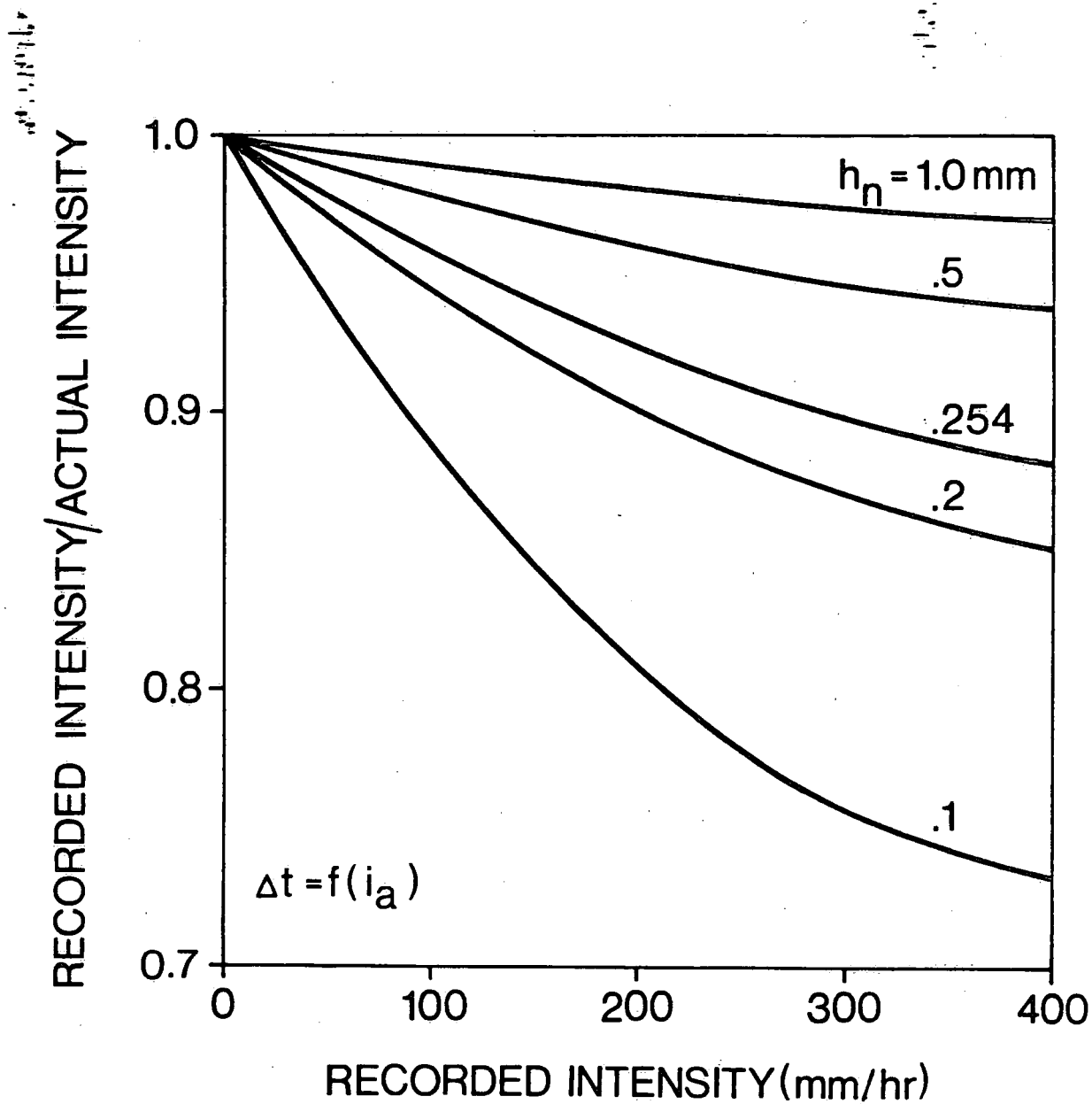Figure 5   Observed and Calculated Calibration Curves for the Raingages Tested

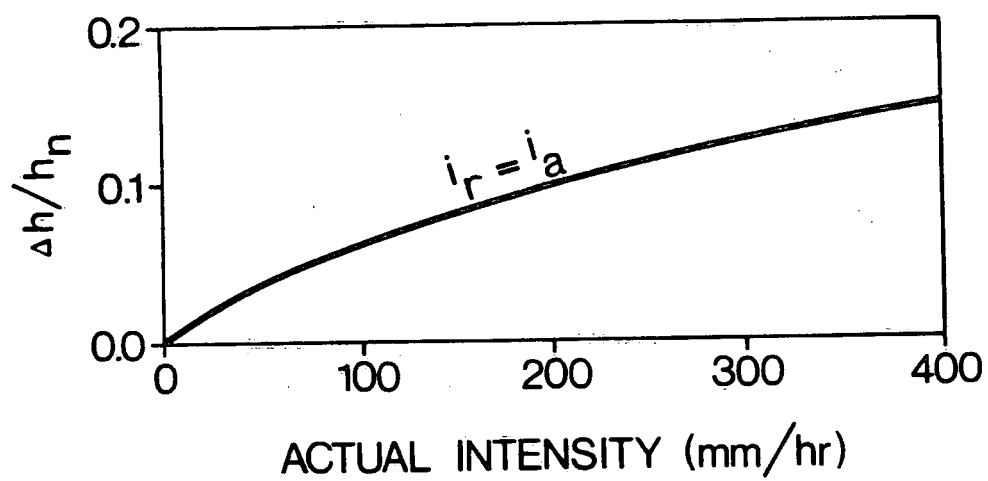Figure 6   General Rating Curves for Different Values of h_n (Varying Bucket Size)

Figure 7   Reductions in the Calibrated Bucket Volume Required to Match Recorded and Actual Intensities

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