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THE INFLUENCE OF RAINFALL
ON THE MECHANICS OF SOIL EROSION,

with particular reference to

SOUTHERN RHODESIA

A Thesis presented by

N.W. HUDSON

For the Degree of Master of Science
in the Faculty of Engineering of
THE UNIVERSITY OF CAPE TOWN

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Material from a number of previous publications by the author is included in this thesis, with the previous approval of the supervisors. Where this takes the form of short quotations reference is made in the text to the appropriate publication. In other cases the material has been rewritten and included with new data in the chapters indicated below.

- 1) "The Design of Field Experiments on Soil Erosion."
Journal of Agricultural Engineering Research,
Vol. 2, No. 1, 1957. Chapters 3 and 14.
- 2) "Erosion Control Research - Progress Report on Experiments
at Henderson Research Station, 1953-56."
Rhodesia Agricultural Journal, Vol. 54, No. 4, 1957.
Chapters 3, 14 and 15.
- 3) "Soil Erosion and Tobacco Growing." Rhodesia Agricultural
Journal, Vol. 54, No. 6, 1957. Chapter 15.
- 4) "Results Achieved in the Measurement of Erosion and
Run-off in Southern Rhodesia." Paper presented to the
Third Inter-African Soils Conference - Dalaba -
November, 1959 Chapter 15.
- 5) "Raindrop Size Distribution, Kinetic Energy and Intensity
of Sub-Tropical Rainfall." Paper No. 94 presented to the
C.C.T.A. Inter-African Hydrological Conference, Nairobi,
January 1961. Chapters 6, 7 and 8.
- 6) "An Introduction to the Mechanics of Soil Erosion Under
Conditions of Sub-Tropical Rainfall."
Address to the Rhodesia Scientific Association,
February 1961. Published in Proceedings and
Transactions of the Rhodesia Scientific Association.
Vol. XLIX, Part 1, pp. 15-25, 1961. Chapters 9, 10 and 11.

APPROVAL BY SUPERVISOR.

I certify that material from previous publications has been included with my approval.

F.A. KILNER.
SUPERVISOR.

THE PROBLEM OF SOIL EROSION AND THE OBJECT
OF THE PRESENT INVESTIGATIONS

CHAPTER I.

THE HISTORICAL BACKGROUND OF EROSION
AND EROSION CONTROL.

1.1. THE HISTORY OF EROSION.

Today soil erosion is almost universally recognised as a serious threat to man's well-being, if not to his very existence, and this is shown by the fact that most Governments outside Europe give active support to programmes of soil conservation. But it is relevant, before making any assessment of present knowledge of erosion, to consider the development of this science which was almost unknown eighty years ago, and now enjoys world wide attention. Bennett (1) and Lowdermilk (2) have both made careful studies of the effect of erosion on early civilisations, and have shown that a major cause of the downfall of many flourishing empires was soil degradation. Although this is clearly evident throughout seven thousand years of history, an awareness of the problem developed very very slowly. We have few records of the earliest Middle-Eastern civilisations, but in such as are available there is no evidence of any conscious association between erosion and the failure of these civilisations through starvation. Later, the Old Testament contains threats and prophecies of streams drying up, and starvation, but few exhortations about good stewardship. A few Greek writers mention land improvement; Homer advocates fallows to rest the soil, and Plato associates floods and erosion with destruction of forests. The Romans had a slightly better appreciation, and Virgil and Pliny recommend what today would be called conservation farming, but right up to the end of the nineteenth century the overall position remained basically unchanged -- there were a few lone voices crying in the wilderness but no general awareness of the problem.

Part of this reluctance to appreciate the significance of erosion may stem from the fact that the early civilisations

all arose on irrigated alluvial plains, and were frequently dependent upon flood deposits of silt for continued fertility. The civilisations of the valleys of the Nile, the Tigris and the Euphrates, which owed their existence to erosion in the headwaters, could hardly be expected to see erosion in the same light as a modern agricultural community.

1.2. THE EXTENT OF THE PROBLEM.

When in 1798 Malthus put forward his theory that the population of the world would outstrip available food resources, he was dismissed as a crank, and indeed at that time the resources and population were in stable equilibrium. However, the world population doubled between 1840 and 1940, and at the same time the industrial revolution put in man's hand the tools, machines, and transport, which made possible the large scale exploitation and exportation of natural resources. The reduction in world resources due to this exploitation, and the increase in demand caused by the population explosion led to the unstable equilibrium of today, when the world's population is only being fed and clothed by the exploitive use of non-renewable resources (Vogt 3, Jacks and Whyte 4). The extent of the destruction of land resources may be judged in the light of the only detailed quantitative survey, that of the United States in 1934 (1) which showed that out of a total of 414 million acres of arable land,

50 million acres were ruined

50 million acres were almost ruined

100 million acres had lost more than half the topsoil

100 million acres had lost more than a quarter of the topsoil, i.e. nearly 75% was seriously damaged. There is little doubt that equally devastating results would emerge from surveys in most countries of the world where agricultural development has been recent.

Stallings (5) points out that in America a big increase in productivity should have arisen from the introduction of improved crop management, better seed, better tillage implements, and greatly increased use of fertiliser. In fact the benefits of these have been so much offset by the decline in fertility due to erosion that average yields have hardly changed in sixty years.

The problem in Africa is particularly serious. Bosazza (6) has shown that geological erosion has always been particularly

the relatively high resistance to erosion of sub-tropical and tropical soils in their natural state, they are particularly vulnerable to reduction in fertility and consequent degradation and erosion.

1.3 THE GROWTH OF EROSION RESEARCH.

The first scientific investigations of erosion were carried out by the German soil scientist Wollny (8), who from 1877 - 1895 carried out detailed studies, using small plots to measure a wide range of effects such as the effect of vegetation and surface mulches on interception of rainfall and on the reduction of deterioration of soil structure, and the effect of soil type and slope on run-off and erosion. Apart from this pioneer work, the lead in erosion research has come almost entirely from the United States of America. Isolated cases of practical application by farmers of mechanical conservation works increased from the 1850's, until in 1907 the United States Department of Agriculture declared an official policy of land protection. The first American quantitative experiments were laid down by the Forest Service in 1915 in Utah, closely followed by those of Miller in Missouri in 1917, which led in 1923 to the first published results of field plot experiments (9). Other similar experiments followed, using essentially the same method, and were given added impetus by the allocation of funds by Congress in 1926, which enabled Bennett and Jones to establish between 1928 and 1933 a network of ten field experiment stations. During the next decade this programme expanded until forty-four stations were operating, and included experiments on mechanical erosion control and run-off from small catchments. Throughout this period the work was limited to applied research, studying problems under field conditions; and although it had been apparent from the earliest days of Wollny that vegetative cover was of vital importance, there was no co-ordinated research programme on the analytical study of the processes of erosion. Pioneer work in this field was carried out in the 1930's by individuals like Bayer (10), Borst and Woodburn (11), and Musgrave (12), and led to the first detailed study of natural rain by Laws in 1940 (13) and the first analysis of the mechanical action of raindrops on

severe in Africa owing to a combination of extremes of climate and steep river gradients. Eden (7) claims that in spite of the relatively high resistance to erosion of sub-tropical and tropical soils in their natural state, they are particularly vulnerable to reduction in fertility and consequent degradation and erosion.

1.3 THE GROWTH OF EROSION RESEARCH.

The first scientific investigations of erosion were carried out by the German soil scientist Wollny (8), who from 1877 - 1895 carried out detailed studies, using small plots to measure a wide range of effects such as the effect of vegetation and surface mulches on interception of rainfall and on the reduction of deterioration of soil structure, and the effect of soil type and slope on run-off and erosion. Apart from this pioneer work, the lead in erosion research has come almost entirely from the United States of America. Isolated cases of practical application by farmers of mechanical conservation works increased from the 1850's, until in 1907 the United States Department of Agriculture declared an official policy of land protection. The first American quantitative experiments were laid down by the Forest Service in 1915 in Utah, closely followed by those of Miller in Missouri in 1917, which led in 1923 to the first published results of field plot experiments (9). Other similar experiments followed, using essentially the same method, and were given added impetus by the allocation of funds by Congress in 1926, which enabled Bennett and Jones to establish between 1928 and 1933 a network of ten field experiment stations. During the next decade this programme expanded until forty-four stations were operating, and included experiments on mechanical erosion control and run-off from small catchments. Throughout this period the work was limited to applied research, studying problems under field conditions; and although it had been apparent from the earliest days of Wollny that vegetative cover was of vital importance, there was no co-ordinated research programme on the analytical study of the processes of erosion. Pioneer work in this field was carried out in the 1930's by individuals like Bayer (10), Borst and Woodburn (11), and Musgrave (12), and led to the first detailed study of natural rain by Laws in 1940 (13) and the first analysis of the mechanical action of raindrops on

the soil by Ellison in 1944 (14). The implications of this are best described by Stallings (5) who says

"The discovery that raindrop splash is a major factor in the water erosion process marks the end of one era in man's struggle with soil erosion, and ushers in another which, for the first time holds out hope for a successful solution to the problem. The exact nature of the effects of raindrop splash is the phase of the water-erosion process that escaped detection during the first 7,000 years of civilisation. It explains why the efforts at protecting the land against scour erosion these 7,000 years have failed. It explains why there is little or no erosion on land with ample plant cover. It explains many things that have puzzled agricultural leaders and practitioners throughout this long and troublesome period."

..... "It remained for Ellison to recognise the true role of the falling raindrop in the water-erosion process. He was the first to realise that the falling raindrop was a complete erosive agent within itself and that little or no erosion occurred when the ground surface was protected by ample cover. He showed that the protective effect of plant cover was due to the fact that it robbed the falling raindrop of its kinetic energy. Ellison's discovery opened a new field of soil erosion science."

The development of this new line of investigation was, however, not straightforward. Some of the pioneer workers were unable to accept the new ideas with scientific impartiality. For example Dr. H.H. Bennett, the first Chief of the Soil Conservation Service, and whose contribution to the knowledge and application of conservation practices is still unequalled, was mistaken when he wrote in 1951,

"Some recently published statements with respect to the effects of raindrop splash have left the impression that this is the most important factor having to do with the erosion process. It is an important factor, but, as already pointed out, it is only one of several factors having to do with erosion on farm lands. As a matter of fact, the cutting and abrasive effect of run-off from rains and the melting of snow are of far more importance than raindrop splash, which makes its principal contribution by hurling soil particles into suspension in the run-off". - (15)

However, the need for detailed research on splash erosion

to support field experimentation was realised by most workers, and the majority of research in this new phase is now taking place in the United States of America, like the earlier field work.

Analytical research was directed onto more specific objective^s by the setting up in 1954 of a national study, which used modern techniques of data analysis and electronic computers to correlate the results of all the field experiments, and pinpointed the main features in the erosion process (Wischmeier 16).

The wide publicity given to the results of the field experiments of the 1920's led to interest in many other countries. In this Africa has been well to the fore. In the Republic of South Africa, Professor D.G. Haylett established the first run-off plots in Africa at the University of Pretoria in 1929. A second group was added in 1936, and similar installations followed at Grootfontein College of Agriculture, Cape Province, and Estcourt Research Station, Natal, in 1938, and Glen College of Agriculture, Orange Free State in 1941. Similar plots to study the effects of wattle management were built by Sherry (17) of the Wattle Research Institute in Natal in 1951.

Elsewhere in Africa, Staples laid down plots in Tanganyika in 1933 (18). Farbrother at the Empire Cotton Growing Corporation research station at Namulongwe, Uganda, developed an unconventional circular run-off plot, since used at Samaru, Nigeria from 1956 onwards. In the French overseas territories in Africa, field experiments were established from 1953 to 1956 in Madagascar, Senegal, French Guinea, Upper Volta, and Ivory Coast.

In Southern Rhodesia, run-off experiments using large plots of several acres were started in 1934, but were abandoned after a few years when gold mining started on the site. In 1953 field experiments were started by the author on the Henderson Research Station, and have expanded until they today constitute the most comprehensive installation in Africa.

Apart from these field plot studies, little work has been done in Africa on the mechanics of erosion. Rose (19) at Makerere College, Uganda, and van Heerden (20) at the University of Pretoria, have studied rain drop splash using artificial rain. The only known study of the subject under conditions of natural rain in Africa is that presently reported by the author, and has been carried out together with the field erosion studies at Henderson Research Station.

Puerto Rico, Australia, and Japan during the last ten years, but the only reported basic research under conditions of tropical or sub-tropical rainfall is that of Mihara (21) in Japan, and Ker (22) in Trinidad.

To summarise, the whole history of erosion research only extends back eighty years, and the vast majority of the applied or field research has taken place during the last forty years. Analytical or basic research only started some twenty years ago, and very little of this has been done outside the United States, or under tropical and sub-tropical conditions.

University of Cape Town

CHAPTER 2.

METHODS OF EROSION RESEARCH

Soil erosion is a complicated process involving many factors, and the amount of soil lost depends upon such variables as the soil type, the ground slope, the length of the slope, the crops grown and the manner of their cultivation, the rainfall, and so on almost indefinitely. Furthermore there are interaction effects between many of the separate factors, so that it is almost impossible to arrive at a precise mathematical solution to the problem.

A number of formulae have been used to introduce some mathematical basis into either predictions of soil loss, or recommendations for land use which will limit erosion to a chosen acceptable value. An example of this method, known formerly as the "Slope-Practice Equation" and more recently as the "Universal Soil Loss Equation" is shown in the following equation of Browning (23) developed from an earlier model by Zingg (24) in which

$$A = P \cdot T \cdot R \cdot E \cdot F \cdot L^{0.6} S^{1.4}$$

where

A is soil loss in tons/year,

P is a factor depending on the conservation practice e.g. 1 for maize in rows straight up and down hill, 0.5 for strip cropping, etc.,

T is a factory reflecting relative erodibility of the soil type,

R is a factor for various standard rotations,

E is the degree of past erosion,

F is a fertility factor representing the amount of fertiliser or manure applied,

L is the length of slope, and

S is the slope of the ground.

The units are very arbitrary, thus S is in degrees, L in hundreds of feet, the remainder are empirical factors whose values for various conditions are chosen so that in combination they give values of A (annual soil loss in tons/acre) which correspond with measured values.

To predict soil loss under a given set of conditions the multiplication of all the factors corresponding to these conditions gives the predicted annual soil loss. Alternatively if a level of permissible or acceptable soil loss is chosen (a common figure is 5 tons/acre) then given fixed conditions such as soil type, slope and length of slope, certain combinations of the remaining agricultural practices will keep A below 5 and so be acceptable, other combinations giving A greater than 5 would not be recommended. Obviously such a method has valuable applications in erosion control and land use planning, but the system hinges upon the suitable choice of the various factors on the right hand side of the equation.

All erosion research is directly or indirectly aimed at providing experimental evidence of the numerical values of the factors, or the manner in which they should be combined, or establishing which factors should be included. One big advantage of the method is that if only half the factors have been evaluated it is still possible to use the equation by taking an intelligent guess at the unmeasured values, and progressively increasing the accuracy by replacing the guesses with experimental evidence as it becomes available. This is more or less what has happened in the United States and in the latest equation published (25) there is some experimental evidence for the choice of values for all the factors, although they will no doubt be improved upon almost indefinitely.

There are two main approaches to erosion research. The first is the method of applied research, using field experimental plots to measure erosion when the controlling factors are set up in a limited number of combinations. The analytical approach uses more precise techniques, either in the laboratory or under closely controlled conditions in the field, to evaluate individual factors in isolation. The methods overlap of course; field plots may be used to study single factors such as land slope, and laboratory studies may be used to study the interaction between rainfall and soil type.

The advantage of field experiments is that they provide practical answers to local problems, and when significant differences are observed these provide the basis for practical recommendations to the farming community. Relative, or qualitative, answers may be quite sufficient for many purposes, such as which of two rotations allows the lesser amount of erosion under the local conditions in a particular area. The disadvantages of field experiments are that they are very expensive to instal and operate, and since rainfall patterns fluctuate from year to year, (particularly in climates where erosion is severe), the experiments must continue for many years before precise conclusions may be drawn. There are several cases where ten years of results have given apparently clear cut and straightforward answers, but the twenty years results have shown that these conclusions were biased as they had been influenced by long term cyclic variations in the climate.

A problem common to many branches of agricultural research, and which applies particularly to erosion research, is the tremendous number of variable factors. An apparently simple problem like the amount of soil lost from a maize crop can only be solved by field experiments if one specifies a particular soil type, slope, length of slope, type of maize, type of rainfall, manner of ploughing, amount of fertiliser and so on. Each variable may have two, ten, or fifty, equally logical and appropriate values, and the number of combinations and permutations is so vast that field experiments can only cover a minute fraction of them.

The advantage of analytical studies is that each variable may be subject^{ed} to careful study using the research techniques of close control of other variables, replication, and statistical testing of the results. When the individual factors have been studied in isolation, the study may be extended to groups of variables and interactions between them. If studies of a variable such as the erodibility of soil types can be done with man-made artificial rain, the collection of information is made very much simpler, cheaper, and quicker. One of the main objectives of the present research study is in fact the collection of information which will lead to the design of a machine which could simulate rainfall, and so be used for such studies either in the laboratory or in the field. This is in effect applying the analytical, one factor at a time, technique to field plot experiments.

The two research methods are thus complementary to each other. The evaluation of each variable by the analytical

method allows more information to be drawn from results of field experiments, and the results of field experiments show which variables require closer analytical study. A good example of this inter-relation is the discovery of splash erosion which, as was shown earlier, is the pivot around which modern research revolves. Borst and Woodburn (26) found in field experiments that layers of vegetative mulch greatly reduced erosion, without fully understanding the reason. This, and similar field experiments, led Ellison (27) in a laboratory study, to observe closely and to photograph the action of water drops falling on covered and uncovered soils. His explanation of the mechanics of splash erosion was then taken back to the field experiments of Osborne (28) and others for investigation of practical ways of applying the new ideas. This is one case where the initiative passed well between the laboratory and the field, but unfortunately the more general pattern has been that research workers have limited themselves to either one or the other phase. Field experiments are usually carried out by agriculturalists and designed to provide practical answers to practical problems. Lack of statistical design, and lack of uniformity usually limit the extent to which results from different field stations may be compared to evaluate, for example, climatic differences. On the other hand critical laboratory studies by soil scientists will be mainly of academic interest if they are not directly linked to field studies. For example, several indices of erodibility for soil types have been based on laboratory determinations of soil properties such as mechanical composition and aggregate dispersion (Lutz 29 and Middleton 30), but have not been used to any great extent because they were not adequately related to experimental field work.

A well balanced research programme must both analyse and synthesise, and progressive moves forward can be expected to come from each alternatively rather than from both simultaneously. In the research programme now being reported, work was for the first four or five years entirely limited to applied field experiments. When sufficient general patterns had emerged, these experiments continued but the emphasis was changed to detailed analytical research for three years, and the resulting information then applied to make more effective use of the field work.

CHAPTER 3.

THE SCOPE OF THE PRESENT EXPERIMENTS.

3.1. DEVELOPMENT AND LOCATION.

In 1951 the Senior Conservation Engineer of the Department of Conservation and Extension recommended that a programme of research on soil erosion control should be established on lines similar to projects he had seen during a study tour of the United States. The very clearly defined objectives and suggested methods (Cormack 31) provided the framework which has not changed materially during the ten years since then. The present author was appointed in 1952 to start this research programme and has remained in charge of it since then.

It was decided that research should first be concentrated on what was thought to be the most serious aspect of erosion in Rhodesia, namely water erosion from arable land in the high rainfall areas of the central watershed. The first stage of direct field experiments was to be followed and supported by the second phase - studies of the mechanics of erosion. The third stage, which will start soon, will be to use the knowledge gained, and techniques developed, to extend the research into other climatic regions with other land use patterns. The three phases are not self-contained, and there is a considerable overlap both in time and subject matter. The first two phases have been completed during the last eight years, and are reported in the present account. The third phase of practical extension will continue indefinitely.

The experiments were sited at Henderson Research Station, a large agricultural research station of the Department of Research and Specialist Services, with facilities for all types of agricultural research, and having a wide range of soils including most types found in the high rainfall part of the country. The Department of Research and Specialist Services generously

made available land, workshop and office facilities etc. This research station lies approximately 20 miles North-east of Salisbury at an elevation of 4,500 feet. The present area is about 6,000 acres, lying between two ranges of hills of completely different geological formation so that almost all land conditions are to be found from flat red clay soils to broken granite kopjes. Average annual rainfall is 34 inches, almost all of which falls in a single summer rainfall season between October and April. Out of season showers are very infrequent and have no significant effect upon erosion or crop production.

3.2. FIELD EXPERIMENTS.

There are four main groups of field experiments, each on a distinct soil type. In 1953 the first group, known as Series I, was established on clay loam soil of the Tatagura series. (Plate 3.1. and frontispiece.) The main experiment (Project I/1) consists of sixteen plots of 1/20th acre each on three different slopes, where run-off and soil losses are measured from maize, maize/green manure crop, and maize/ley rotations. Previous publications report the design, installations, and operation of the recording and measuring apparatus and equipment, (Hudson 32) and the rotations and cropping practices (Hudson 33). On the same site Project I/3 evaluates the separate effects of raindrop splash and surface flow, using three plots of 1/100th acre with different types of protective cover.

Other experiments in this Series are directed to practical problems not directly related to the present thesis, such as the effect of varying distance between contour ridges (Project I/2), the effects of long term grass leys (Project I/4) and the effect of alternative methods of ploughing between contour ridges (Project I/5).

In 1954 the experiments were extended to Series II, where on red clay soil of the Mazoe series, Project II/6 follows closely the pattern of the main experiment on Series I, using eleven plots of 1/20th acre on two slopes to measure the effects of similar rotations centred around maize production. (Plate 3.2.).

In 1955 similar experiments were sited on two types of granite sand soil. On Series III, Project III/10 has nine plots of 1/20th acre on a shallow badly drained sand, (Plate 3.3.) and on Series IV, Project IV/12 has four similar plots on deep well-



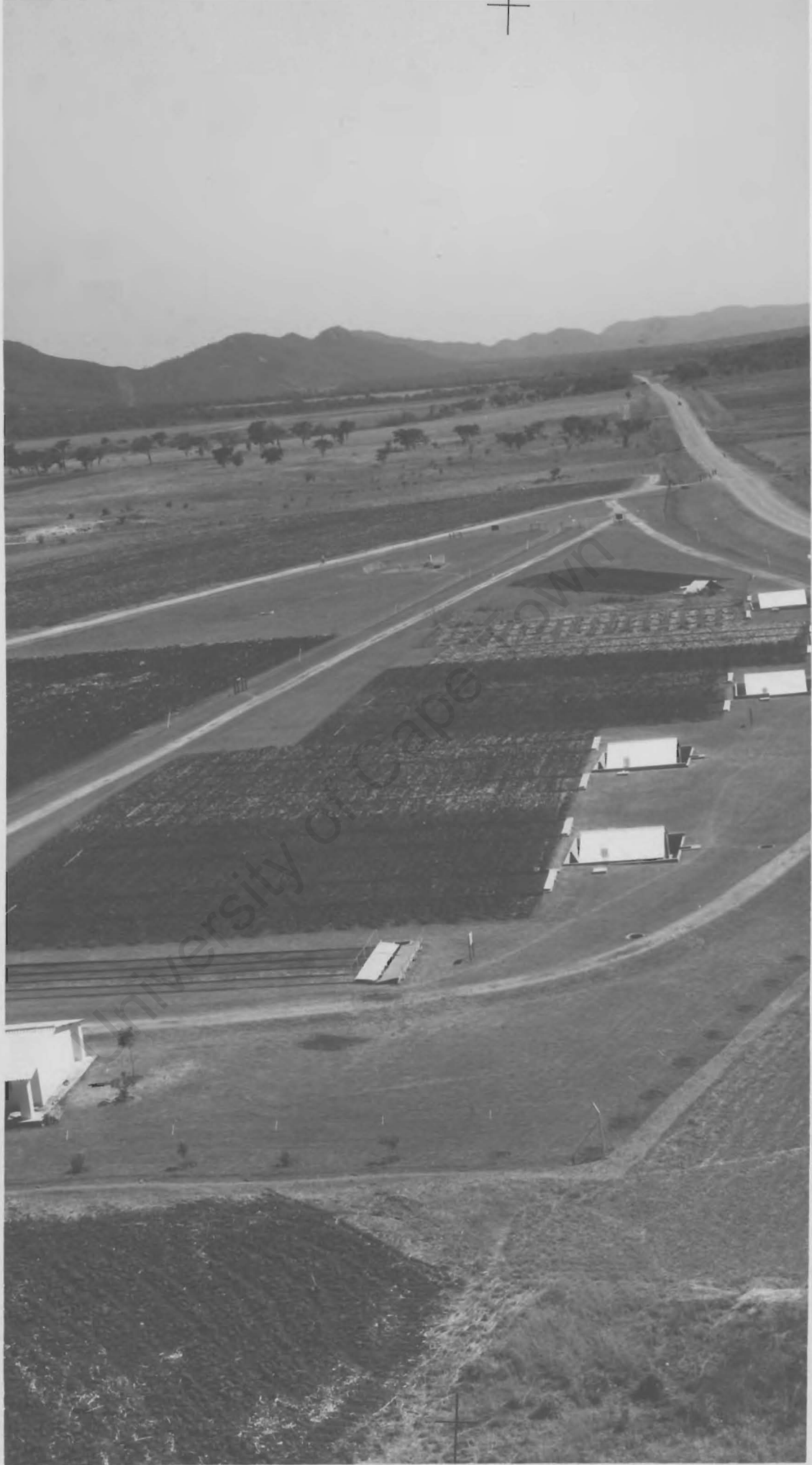


Plate 3.2 Series II Experimental Site (Photo J. Rau).



Plate 3.3. Series III Experimental Site.



Plate 3.4. Outside of Rainfall Laboratory.

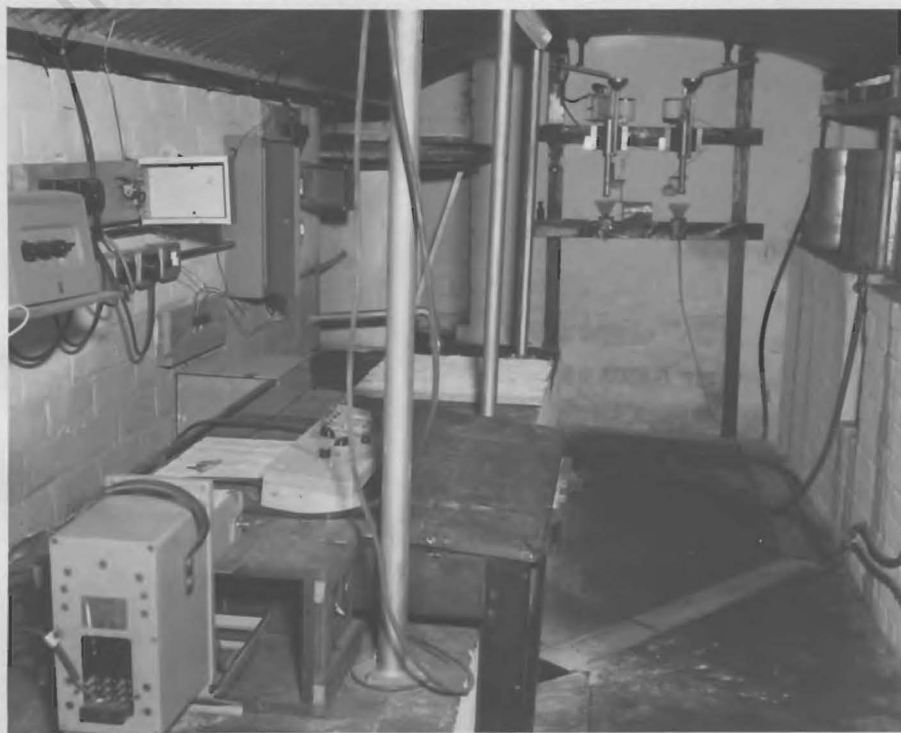


Plate 3.5. Inside of Rainfall Laboratory.

Splash erosion and wash-off erosion were measured simultaneously in the rainfall laboratory using miniature run-off plots, and on a field scale run-off plot a short distance away. The rainfall laboratory studies were carried out over three rainy seasons from 1958 to 1961.

3.4. OBJECTIVES OF THE EXPERIMENTS.

The purpose of the analytical part of the studies may be expressed by asking the question "What are the features or characteristics of sub-tropical rainfall which determine its ability to cause soil erosion?". Before considering this question as a whole, an answer is required to the first part - "What are the characteristics of sub-tropical rainfall?". It was shown in Chapter 1 that the importance of raindrop splash as an erosion agent has only been appreciated in recent years. Detailed studies of rainfall properties in relation to erosion, arising from this appreciation, are therefore few, and moreover have been chiefly concerned with types of rainfall other than the high intensity convective thunderstorm rain of the tropics. Since the necessary information is not available, the first object of the present studies is to fill this gap. The experiments on rainfall, and the information obtained, are described in Part II (Chapters 4 - 8).

The next objective is to establish the relation between rainfall characteristics and erosive power, and to define the erosive power in quantitative terms. In addition to rainfall, erosion is influenced by many properties relating to the soil or to treatment imposed on the soil, but the approach will be first to hold constant all soil properties while relating erosive power to physical properties of rain, and subsequently to test the relation under various soil conditions. The potential ability of rain to cause erosion is defined as "Erosivity", and the soil's vulnerability to erosion is defined as "Erodibility". A value on the scale of erosivity is based solely on rainfall properties, and to this extent it is independent of the soil. But a quantitative measurement may only be made when erosion occurs, and this involves the erodibility of the eroded materials. Similarly relative values of erodibility are not influenced by rain, but may only be measured under rain which has erosivity. Thus neither is independently quantitative, but each may be studied quantitatively while the other is held constant.

There is also the possibility of interaction between the

two effects, i.e. when two different storms fall on sand soil, the mathematical ratio of their erosive powers may not be the same as if they fell on clay soil. Since by definition erosivity depends solely on physical properties of rain, and erodibility on physical soil conditions, such interaction is unlikely to be of any consequence. Before considering the complicated interplay between soil effects and rain effects the information on rainfall properties must be related to erosive power, and this is done in Part III (Chapters 9 - 11).

3.5. APPLICATIONS.

The understanding of the relations between erosion and rainfall allows two practical applications; one of which leads to further advances in the analytical approach; the other increases the information obtainable from the field experiments.

The analytical application of a quantitative measure of erosivity is in the design of critical experiments to evaluate individual factors in the erosion equation. For example, to measure the effect of soil slope or gradient, test containers of soil may be placed on a table which can be adjusted to provide various slopes, and the soil then subjected to simulated rainfall from some type of spray apparatus. This is a very convenient technique, but the results are liable to be meaningless if the erosive power of this simulated rain bears little relation to that of natural rain. A measure of the erosive power of natural rain is thus a primary requirements in the use of artificial rain. Similar critical experiments using natural rain are equally handicapped by the absence of a measure of the rain's erosivity.

The information obtained on the nature of sub-tropical rain and its erosion effects, made it possible to start in December 1960 on exploratory designs for an artificial rain-making device. These were developed in the winter of 1961 at the Hydraulic Laboratories of the University of Cape Town to the stage of a practical working prototype suitable for field testing. The requirements and the design of this instrument are discussed in Part IV (Chapters 12 and 13).

In the field experiments, which involve crop rotations and crop management, the ability to assess quantitatively the erosive power of rainfall means that much undesirable variation can be eliminated. For example, an experiment might be designed to test the effectiveness of stubble mulching, and to see how this effectiveness differs at the beginning and end of the growing season. It would be remarkably fortunate if exactly equal storms fell at the beginning and end of the season and so allowed a direct comparison.

In fact the most noticeable feature of sub-tropical rainfall is the almost infinite variety of seasonal patterns. A quantitative measure of erosivity would allow the reduction of dissimilar storms to a common base, and so allow an assessment of the effectiveness of mulching throughout the season. A similar problem occurs in rotation experiments, such as one designed to compare the annual erosion from successive crops of tobacco, i.e. to measure progressive deterioration of the soil. This can only be evaluated accurately if the successive rainfall seasons are similar, (or of similar erosivity), and this also is an unlikely possibility in Central Africa. If the erosivity index for storms can be summed to give a seasonal index, then the varying seasons can be reduced to a common base for comparison of annual losses. There are innumerable applications similar to these two examples (Hudson, 34) because in any field experiments on erosion the number of variables is so large that complete experiments of factorial or Latin square design are seldom practical. The ability to extract fuller information from the results of storms or seasons of differing degrees of erosivity is therefore of the utmost importance. Some examples of this application are given in Part V (Chapters 14 and 15).

PART II.

RAINFALL STUDIES.

CHAPTER 4.

RAINFALL CHARACTERISTICS AND REVIEW OF PREVIOUS STUDIES.

It has been obvious from the very earliest days of erosion research that the correlation of soil erosion with total amount of rainfall is very poor (in fact it is merely an association), and that more specific measures are required to describe rainfall in its relation to erosion. The features or characteristics of rain which may affect its erosivity are total quantity, accompanying wind, various properties related to intensity, and the size, size distribution, and impact velocity, of individual drops or groups of drops. The size, or mass, and velocity may be combined and expressed as momentum or kinetic energy. Each of these features must be examined to see whether sufficient, or sufficiently accurate, information is available, and where this is not so, to determine what methods or techniques should be employed to obtain the required information.

4.1. QUANTITY OF RAIN.

Any measure of rainfall amount is a sample, and so associated with the inevitable problems of sampling, namely, "Is the sample representative of the whole?" and "Is the sample measured accurately?". Discussion of the main factors involved, i.e. number, distribution, and types of raingauge, and discussion of the voluminous literature on the subject are outside the scope of the present investigations. An excellent review of raingauges and recorders is given by Kurtyka (35) in a most detailed study with 193 illustrations and 1097 references. For most erosion studies it is sufficient to adopt a constant, accepted, practice, and in the present investigations the standards used are those of the Department of Meteorological Services, Federal Government of Rhodesia and Nyasaland. The standard non-recording gauges used are five inch diameter (tropical pattern with deep funnel to prevent splash), set vertically at a height of 3' 6" above a turf surface, and free from surrounding obstacles at approach angles of more than 30° with the horizontal. Separate gauges are used for each experimental site if the sites are more than 300 yards apart.

In addition each site has an autographic recording gauge. The standard instrument of the Meteorological Department is used, - the Cassella natural siphon, with five inch diameter rim, siphoning every one inch, recording on a clockwork driven 24 hour chart 12 inches long. Intensity may be measured to some extent from the rate of increase of the chart trace, but the estimation of short periods at high intensities is not accurate, and special intensity recorders were also used.

The effects of wind on rain measurements were considered, and the instruments used to measure the angle of inclination and direction in azimuth are discussed separately in Chapter 6.

4.2. INTENSITY OR RATE OF RAINFALL.

There is considerable evidence of a close association between erosion and intensity, and intensity is particularly important as a potential parameter of erosivity because it is the only feature of rainfall which, in addition to amount, is frequently recorded at conventional meteorological stations. Data on occurrence and frequency of intensities is nowadays recorded on most meteorological stations, and no erosion experiments would be properly equipped without some form of intensity recorder. Any erosivity index based solely, or primarily, on some function of intensity has thus a greater scope for its application than an index based on any other characteristic. An index based on, for example, kinetic energy would still be extremely useful even if it required new instrumentation to measure the kinetic energy, but would only be applicable after the collection of new data, and so is less useful than an index based on intensity.

Two definitions of intensity are commonly used and the difference between them must be clearly established. In the cloud physics branch of meteorology, dealing with rain in relation to surrounding air space, it is usual to describe amounts of rain as the volume of raindrops (in c.c.) contained in unit volume of air (one cubic metre). The corresponding definition of intensity is the rate of change of this volume of water with respect to distance fallen in unit time. This means that the total intensity is a summation of a function of each drop and its own fall velocity. This definition is particularly relevant to radar studies of rain.

Agriculturalists, Conservationists, and Engineers, who are concerned with the rate of rainfall arriving at the plane surface of the ground, express intensity as the volume of rain arriving on unit area of this surface in unit time. Both definitions have similar dimensions, i.e.

$$\frac{L^3}{L^2 T} \quad \text{and} \quad \frac{L^3}{L^3} \times \frac{L}{T} \quad \left(\text{both reducing to } \frac{L}{T} \right) \text{ and it is possible}$$

to convert from one to the other if the drop size distribution and fall velocities are known. The engineer's concept of intensity has been used throughout the present study, i.e. the rate of rainfall arriving at the ground, but the meteorologist's definition is explained as it is the basis of the theoretical deductions of intensity or drop size distribution to which reference will be made later.

Measurements of intensity sufficient for meteorological purposes are normally obtained from recording raingauges where successive increments of rainfall are recorded as a cumulative total on a clock driven chart whose speed varies according to the frequency with which the chart is to be changed, usually daily, or in remote or inaccessible areas, weekly or monthly. Three main types of mechanism are employed. The direct weighing gauge, used extensively by the United States Weather Bureau, passes the rain from the collecting funnel to a vessel whose weight is recorded with a suitable linkage to give readings in inches (or mm.) of rain. The tilting bucket type records in positive steps each time the quantity of rain fills a bucket and causes it to tilt, moving the pen through a mechanical linkage. Both these may have a mechanism to reverse the linkage when the pen reaches the top of its travel, so there is no upper limit to the amount which may be recorded. The third type, used in these experiments, retains the collected rain water in a chamber containing a float linked to the pen arm. The pen records the increase in height of water in the chamber, with a siphon to empty the chamber and so return the pen to zero at increments of usually one inch of rainfall. In all these the intensity is computed from the rate of change in the quantity of rainfall recorded, i.e. the gradient of the recorded line. This indirect measurement is suitable for averaging the intensity over fairly long periods, but when the time interval is short the method becomes very laborious, and is not very accurate.

A number of direct reading intensity recorders have been constructed for experimental purposes. Lewis & Watkins (36) tested two models both based on continuous recording of the weight of the rain retained at any one time in a vessel through which the collected rain passed. Both were satisfactory, and superior to indirect machines recording cumulative quantity of rain. Adkin (37) passed the rain from a collecting funnel through a special dropper which formed large drops of constant size. The drops fell onto wire contacts and triggered a monostable vibrator which operated a pen-recorder, the rate of dropping giving a measure of intensity. Ker (22) constructed a table which rotated in jerks to place a large number of collecting vessels one at a time under the outlet from a collecting funnel. The intensity was calculated from the measured quantity collected in a known time, but

this could only give spot samples for short periods. Farbrother (38) constructed a very simple and effective instrument, which is a variation of the constant weighing method. Rain from the collecting funnel passes into a cylindrical container with a narrow vertical slit up one side. The level rises to such a point that the inflow from the funnel balances the outflow through the slit, and the quantity held at any one time is a measure of the rate of inflow. The cylinder is mounted on a cantilever spring and the deflection caused by the weight of water in the cylinder is recorded directly by a pen arm. The instrument is calibrated directly by pouring water in at measured rates, and measuring the consequent deflection. This same basic principle of balancing the inflow and outflow is used in the commercial 'Jardi' intensity recorder of Messrs. Cassella, and also in the instruments which were designed, built, and supplied, by the Federal Department of Meteorological Services for the present experiments. The instrument is shown in its normal housing in Plate 4.1., and in the underground rainfall laboratory in Plate 4.2. Figure 4.1. shows the operating parts in diagrammatic form. Rainwater passes from the collecting funnel A through pipe B, designed to eliminate air locks and swirl effects, to funnel C from where it is led to the bottom of float chamber D through vents designed to avoid swirl and eddies. The water level rises, lifting float E, and the taper needle F, to such a point that the gap around the needle where it passes through the circular orifice G is large enough for the outflow to equal the inflow. As the rate of flow (intensity) rises and falls so does the float and pen arm, constantly seeking a new balance. The taper on needle F is so arranged that the vertical movement of the pen gives a direct reading of the intensity with linear scale. A large collecting funnel (two feet diameter) gives a sufficiently large volume of water to overcome any frictional resistance. The sensitivity to small changes in water level in the float chamber is increased by attaching the pen arm support to a counterweight via a pulley and light flexible cable. Guides (not shown) locate the float, taper needle and the rod carrying the pen arm. Any desired chart speed may be used to record intensity, or as is shown in Plate 4.2. two pens may record simultaneously on charts with different chart speeds. Figure 4.2. shows traces of the same storm, recorded at various chart speeds for different purposes. These instruments have proved ideally suitable for the present experiments, and in addition to recording intensities are used to trigger other recording or sampling instruments, by means of low voltage micro-switches linked to high voltage relays which operate the power circuits. This switch gear is described in Chapter 8.



Plate 4.1. Intensity Recorder as Normally Used.

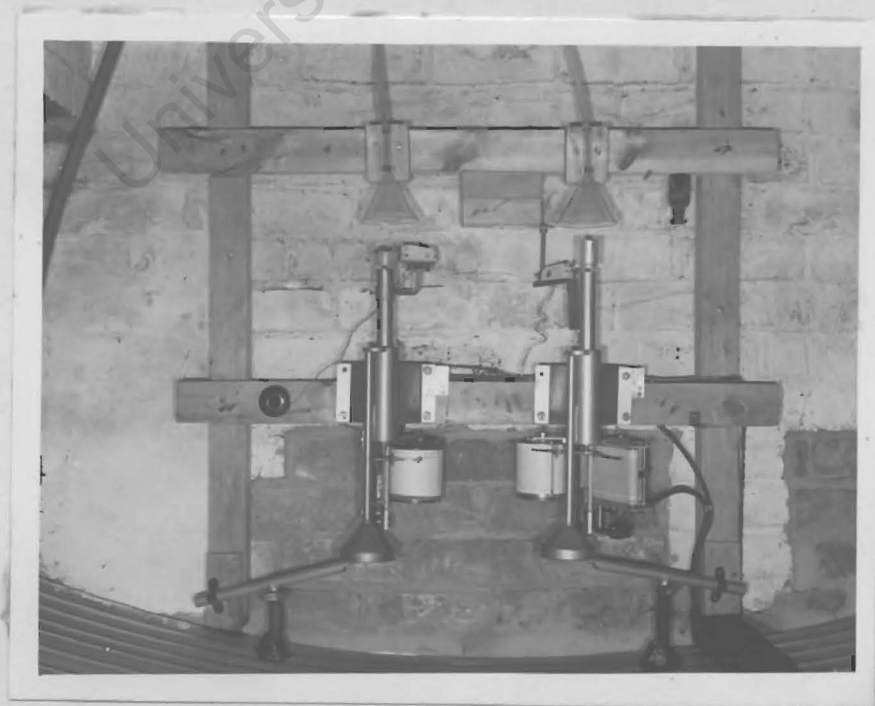
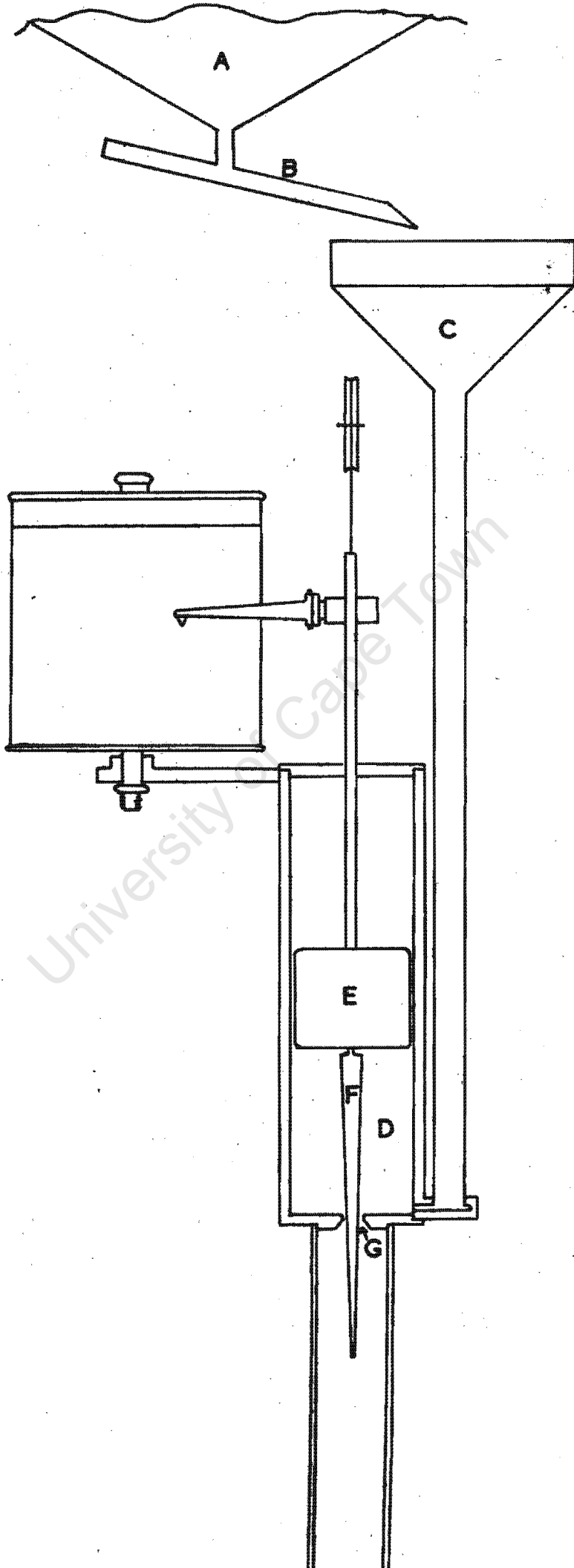
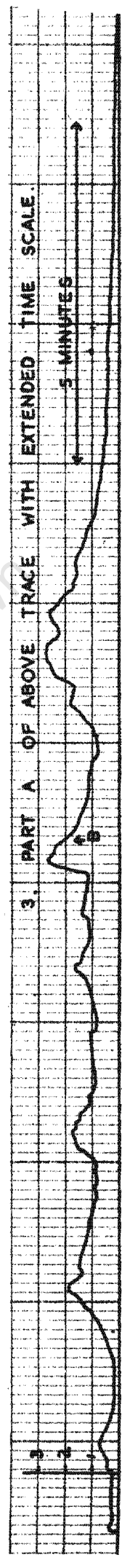
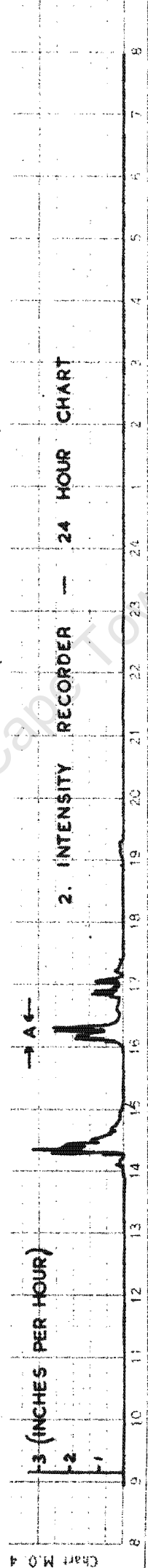
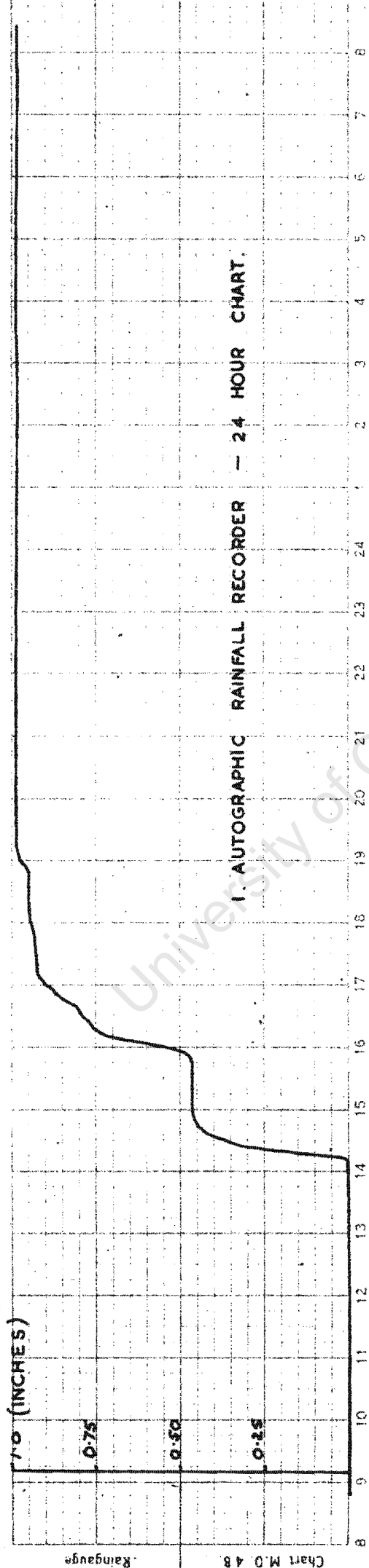


Plate 4.2. Intensity Recorders in Rainfall Laboratory.





4. POINT B WITH TIME SCALE FURTHER EXTENDED.



4.3. MEASUREMENTS OF FALL VELOCITY OF WATER DROPS.

As two independent studies (Laws 39, and Gunn & Kinzer 40), using quite different experimental methods, show very good agreement, these values are considered acceptable for use in the present experiments without experimental verification, and earlier or less appropriate methods are only reviewed very briefly.

4.3.1. Mathematical Calculation.

Detailed treatments of the mathematical theory of the velocity of falling drops or spheres are given by Best (41) and Spilhaus (42) and are reconcilable with the experimental results of Laws and Gunn. Hirschfield (43) developed the semi-empirical formula of Schmidt (44) and found a good agreement with Laws' experimental values for small drops up to 1.6 mm. diameter. Best includes a suggested calculation covering the variation in velocity due to the effect of increased altitude. No experimental confirmation is known, but the effects are small, and have been incorporated in the results of the present studies. For the altitude at which the experimental work was undertaken (4,500 feet), Best computes a correction factor for "summer tropical atmosphere" of 1.051 for drops of diameter 0.3 - 6.0 mm., 1.033 for diameters 0.3 - 0.05 mm., and 1.021 for drops smaller than 0.05 mm. diameter (relative to 1.0 = terminal velocity at sea level).

4.3.2. Early Experimental Determinations.

Mache (45) in 1904 used a photographic technique chiefly noteworthy for the fact that it was the forerunner of that successfully used by Laws nearly forty years later.

Schmidt (44) in 1909 measured directly the time for water drops to fall a fixed distance. Two discs were mounted a fixed distance apart on a vertical spindle rotated at constant speed. A drop falling through a narrow slot in the upper disc, landed on the lower disc which rotated during the period of fall. The amount of angular rotation could be measured from the position of the drop marks on the lower disc, and hence time of fall and velocity were calculated. The results from measured drops were used to create a semi-empirical formula applicable to other drop sizes. Lenard (46) and Litzner (47) extended these early German studies but did little more than confirm the results in a fairly general way. Flower (48) attempted a direct mechanical method by registering the impact effect of drops of known size on a sensitive ballistic torsion balance.

4.3.3. Later Experimental Studies.

All these early measurements agreed reasonably well

considering the simple apparatus used, and so when in 1941 Laws (39) obtained values 15% higher, using modern high speed photography, a very careful search was made for possible errors. Laws could find none in his own experiments, and his values were later confirmed by the independent studies of Kinzer and Gunn(40). The method of Gunn (49) was that water drops were given a slight electric charge and allowed to fall through induction rings which gave an electrical impulse when the drop fell through them. The impulses were fed through amplifiers to an oscillograph so that the time to fall the measured distance between the two induction rings could be measured very accurately. Kinzer and Gunn's results differed from those of Laws by less than 3%, and have been used for computing results in the present experiments.

4.4. DROP SIZE, AND DROP SIZE DISTRIBUTION.

As previously mentioned, earlier studies have been confined almost entirely to temperate climates, or low intensity rain, and so it is clear at the outset that new information is required. The methods and techniques used previously must therefore be carefully reviewed to see which, if any, are suitable for the present purpose, bearing in mind the particular requirements of the present experiments. These requirements are:

- 1) Since from earlier experiments a wide scatter appears to be a feature of size and size distribution, a large number of samples will be required, such as all rains of at least one and probably more seasons. The method must be such that the physical processing and computation of results from a large number of samples is possible. On the other hand, one feature of the present experiments (and common to most of the so-called 'underdeveloped' countries) is the ready availability of assistants capable of quantitative measurements not involving a high standard of selective judgement or estimation. A process involving a very large number of simple operations is thus not unsuitable on those grounds alone, in contrast with some countries where the extraordinarily high cost or non-availability of such labour might well make such a process impracticable.
- 2) One of the distinguishing features of tropical rainfall is the very high intensities which occur. Any apparatus used must be suitable for use in intensities up to 12 inches per hour. The high intensities and very heavy storms only occur infrequently; they are largely unpredictable; and liable to occur at any hour of the day or night. Without a large team of observers to operate the experiments throughout 24 hours of the day for

several months, some system of automatic, self-actuated or continuous recording apparatus is required. The importance of catching every one of the few peak storms means that such automation must be very reliable.

The wide variety of techniques which have been used to measure drop sizes, either of natural rain or other liquid drops, has therefore been compared against these requirements.

4.4.1. Direct Collection and Weighing.

Since drop size influences fall velocity, the distribution of drop size, or at least the distribution among certain groups of sizes must be measured, and the total mass of all drops is of no interest. The direct collection of individual drops for measuring as individuals is therefore required. The preservation of individual drops by catching them in a heavier fluid has been used successfully in laboratory studies. Gunn and Kinzer (40) applied this to determine the size of water drops whose fall velocity was being measured, using a measuring microscope to measure the drop diameter. Tate and Marshall (50), studying the atomisation of fuel oils, used a similar method, measuring enlarged photographs of very small drops caught in oil in glass bottomed containers. Neuberger (51) reports that some use was made of this method by Kohler and Hageman in Germany to record raindrops, but generally it is not suitable for natural rainfall studies because of the probability of drops coalescing in the catching fluid. Taylor and Harmon (52) used the method of catching water drops in a tank of super cooled liquid and obtaining drop sizes from the rate of fall of the frozen drop through the super-cooled liquid. Longwell (53) used a similar freezing technique to study drop size of atomised fuel oils. Maintaining the liquids at very low temperatures under field conditions would present considerable difficulties, and even if these could be overcome the technique is not suitable for taking a number of replicated samples at short time intervals. None of the direct weighing or measuring techniques appear capable of development for field use on a large scale.

4.4.2. Radar.

The amount of reflection of radar waves is a function of the number and size of water drops, and much progress has been made in recent years by meteorologists using radar equipment both on the ground and mounted in aircraft. Estimates of rainfall intensity and amount are reported by Austin and Williams (54), Marshall (55), Smith (56), Twomey (57), Wexler (58), and Jones (59). A general estimate of drop size distribution was obtained by Marshall and Palmer (60), and

developed further by Spilhaus (61), but a comparison of radar results with those obtained by other methods, showed that the accuracy of radar methods is far below that required in the present experiments.

4.4.3. Photographic Methods.

Since the pioneer work of Mache (45) in 1904, photographic methods have been used to study falling drops, and the use of electronic flash apparatus, stroboscopes, and very high speed cameras is now a highly developed science (Edgerton and Killian, 62), but these are essentially laboratory techniques. Simpler high speed cameras have been successfully used to measure the velocity of artificial drops and natural rain by Laws (39), and of drops from irrigation sprinklers by Green (63), but in neither case were measurements of drop size sufficiently accurate. In Germany recently Schladerbusch and Czeratski (64) studied both size and velocity of drops from irrigation sprinklers and achieved successful results in the laboratory. Ekern (65), photographically recorded the deformations of falling drops, and Blanchard (66 and 67), photographed the processes of drop formation and break-up of drops suspended in an airstream, but these were also laboratory methods not applicable to large numbers of drops in natural rain.

The only known case of photographic techniques being successfully used to record the size of natural rain is the work of Jones (68 and 69) in Illinois. This machine meets all the requirements for the present experiments. It is automatic, can sample high intensities, and gives a good estimate of the instantaneous drop size distribution in a cube of air space just above ground level, but the cost of the high quality photographic, illuminating, and other auxilliary equipment, was far beyond the resources available.

4.4.4. Calculation of Empirical Formulae.

Best (70) in 1950 constructed theoretical formulae for various parameters of drop size distribution, for example:

$$\text{Median Drop Diameter} = 0.69^{\frac{1}{n}} a$$

n and a are constants relating to a particular fall of rain, and values were calculated using all previously recorded data. However, there were considerable variations even at the low values of intensity which had been sampled, so extrapolation to much higher intensities is not justified without experimental confirmation. Similar exercises have been carried out by Spilhaus (42), Neuman (71) and Horton (72) but suffer the same defect, that deductions based on theoretical grounds, or measurements at intensities of 0 - 3 inches per hour, should not be extrapolated up to values of 10 or 12 inches per hour without experimental evidence.

4.4.5. Electronic Devices.

A number of widely differing methods may be grouped for convenience under the deliberately loose term 'electronic devices'. Adler et al. (73) mounted negatives showing photographic drop images on a revolving drum which passed between a light source and a 'Photo-tube' (photo-electric cell?) from which the impulses were amplified, sorted by level selectors, and counted. Very rapid counting in fifteen size groups was possible, but the difficulty lies in obtaining the photographic image. Adler was dealing with very small droplets which could be caught on coated slides and then photographed, but difficulties arise when large drops are involved. A number of similar scanning devices have been produced (Courshee and Trickett, 74; Liljedahl and Strait, 75) to study drops from irrigation sprays, and flying spot scanners using the principle of a television camera are now commercially available, but are all dependent upon producing a suitable image.

Mason and Ramanadham (76) designed and used a 'photo-electric raindrop spectrometer'. A sample of falling raindrops passes through a light beam and the scattered light is focussed on the cathode of a photo-multiplier cell whose output impulses are sorted into group sizes and counted. The device has operated intermittently at low intensities in England but fails to fulfill the requirement of a high degree of reliability over extended periods of operation. A very similar principle of causing drops to interrupt a light beam focussed on a photo-electric cell linked to an oscilloscope, was used in an aircraft-mounted instrument by Cunningham (77). This recorded individual drops in very rapid succession as the aircraft flew through rain, and could not be applied to simultaneous recording of a large number of drops at a fixed point.

Smith (78 and 79) caused drops to pass between the plates of a condenser, and from measurements of the induced electrostatic charge deduced both the natural electric charge and the size of the natural raindrops. The primary object, successfully achieved, was the study of electric charge, but a practical instrument for field measurements of size does not appear to have been developed. All electronic devices must be ruled out as being unable to fulfill the requirement of reliability during extended periods of operation.

4.4.6. Measurement of Impact Effect.

Instruments which depend on recording the impulse transmitted from a diaphragm, such as a microphone, when it receives the impact of a single drop have been mounted on aircraft by Cunningham (77) and I. Katz (80) and R.E. Katz (81), and on rising balloons by Cooper (82) and Fujiwara (83). These record single drops, or small groups of

drops, entering a small aperture, and depend upon passage through a large volume of rain to give a large representative sample, and so are unsuitable for fixed operation on the ground. Maulard (84) used the diaphragm of a telephone earpiece as the receiver of a recording device to count the number of raindrops, but neither this nor an earlier version of the same principle by Schindelaur (85) gave an accurate assessment of drop size. The use of a large diaphragm or collector to measure the combined impact effect of a large sample is discussed in Chapter 7, but the immediate problem is to measure the individual drop sizes within a sample. To achieve this from recorded drop impacts would require an impractically large number (of the order of 100) of separate sensing elements since the minimum area required for sampling drop size distribution is estimated to be about one square foot. (Private communication from the Director, Federal Meteorological Department).

4.4.7. Measurements of Spots Caused by Raindrops.

One of the most frequently used methods for measuring both size and size distribution is to catch the drops on some material which retains a mark or impression which can be measured, and whose size can be related to the size of the drop making each spot. This method was first used by Lowe (86) who in 1892 caught raindrops on flat sheets of slate, ruled into squares for ease of measuring the size of the splashes.

Very small droplets may be caught on glass slides coated with a substance such as magnesium oxide in which a minute crater is formed by each droplet. The size of the crater, and hence droplet size, is measured under a microscope. (Hogan, 87; Squires and Gillespie, 88). Preliminary size sorting into groups was included by May (89) by means of orifices to regulate the approach speed. Such methods are not suitable for large drop sizes because of the splashing effects when the drop strikes a solid surface.

This problem of splash was overcome by Blanchard (90) and Boucher (91), who used fine mesh screens (actually ladies' nylon stockings) coated with a powder of contrasting colour such as lamp black or white icing sugar. Raindrops pass through the screens without splashing and each removes the powder from an area whose diameter corresponds to that of the drop. The screens were photographed for permanent record and ease of measuring the spots, but the measurement could be done directly on the screens. This is a very precise method and suitable for spot sampling but not for automatic or continuous sampling because the preparation of the screens is time consuming and must be done immediately before exposure, or alternatively, previously prepared screens must be stored in constant humidity chambers.

The third variation of spot or stain measurements, which has been used in the majority of size studies both of natural rain and under laboratory conditions, consists of catching the drops on sheets of partially absorbent material such as blotting paper, and measuring the size of the spots produced by each drop. In laboratory studies a soluble dye (Bean & Wells, 92) or fluorescent chemicals (Hanson, 93; Liljedahl & Strait, 75) added to the water makes the spot permanent and easier to measure. The same effect is achieved in natural rainfall measurements by lightly dusting onto the surface of the paper a small amount of a powdered water-soluble dye such as Rhodamine or Methylene Blue (Blanchard - 94, 95, 96). This spot method was extensively used by several German meteorologists who carried out many experiments on natural rainfall. (Weisner, 97; Lenard, 46; Defant, 98; Becker, 99). Of these Weisner's work is of interest in the present studies because it is the only other known study which includes tropical thunderstorms, and both Weisner and Defant considered probable sources of error. This early German work was continued by Niederdorfer (100 and 101) who grouped natural raindrops into no less than 97 size groups. When American meteorologists considered using the technique, Neuberger made a careful study of possible errors (51). He showed that inherent differences in the absorbing qualities of individual sheets of blotting paper or filter paper may cause appreciable errors, even when using a high grade paper, and that the ratio of the drop to the stain it produced is a function of both the humidity of the paper, and of the velocity with which the drop strikes the paper.

In spite of these serious defects in the method, it continues to be widely studied, but Neuberger's arguments are strengthened by the variation between the calibration equations suggested by different workers. The expression used to relate the diameters of the drop and the stain is

$$D = aS^b$$

where D is equivalent drop diameter (i.e. diameter of a spherical drop having the same volume as the actual drop which is distorted by wind resistance during fall.

S is the average stain diameter

a is a constant depending on the thickness and absorptive capacity of the paper

b is a constant for which suggested values are 0.66 by

Fournier D'Albe & Hidayetulla (102), 0.84 by Jarman (103)

and from 0.75 - 0.93 depending on drop size (Magarvey, 104).

Recent applications of the technique to non-meteorological problems have been made by Lee (105) in a study of fuel atomisation, by Gunn (49) in laboratory studies of drop velocity, by Levine (106), Riley (107), and Shanks & Paterson (108 & 109), in the testing of irrigation sprinklers, and Davis & Elliot (110) for measuring

aircraft-laid sprays.

Successful studies of the size and size distribution of natural rain using a number of variations on the same basic method have been undertaken by Atlas & Flank (111), Anderson (112), Kelkar (113) and Marshall and Palmer (55 & 60), but all of these were intermittent spot sampling of low intensity rain and so do not contribute to the solution of the immediate problem. Kelkar eliminated errors due to variation in the absorption of the paper by using a glazed paper, and claims that this is "an innovation and a distinct improvement".

A continuous recording instrument using an unrolling spool of sensitised paper was designed for use in aircraft by Bowen (114), but was intended for measurements of comparative values of total water content at various cloud levels, and the diameters of individual drops could not be measured accurately.

In more accurate instruments for ground use Bowen & Davidson (115) allowed rain to fall through a sampling aperture into a horizontal wind tunnel where an air stream deflected the falling drops onto a power-driven spool of sensitised paper. The sideways deflection is proportional to the mass and velocity of the drop and so the position on the paper as measured from a datum line is a measure of the size of each drop. A calibration is obtained by measuring the size of stains at various distances of deflection from the base line. The same instrument was modified by Turner (116), who wished to establish a relation between drop size and salinity. The paper strip was replaced by a number of collecting funnels placed to catch groups of drops deflected varying distances by the air stream. The total volume of rain collected in each funnel thus measured the volume of raindrops falling within a relative size group.

Several recording instruments have been designed and used by Blanchard (94, 95, 96), and Spencer & Blanchard (117) during the operation of Project Shower in Hawaii. It was desired to measure drop size and distribution at different elevations in fairly inaccessible mountainous country and a light portable recorder was required which would measure a continuous sample for a few minutes each time, at regular intervals throughout the day. Rain fell through a small sampling aperture onto a narrow strip of dye-impregnated paper wound on film reels. A time switch started the battery driven motors used to unwind and expose sections of paper for short periods at predetermined intervals. Later models included a shutter to close off the aperture when not recording, and a heating lamp to dry the exposed paper before it passed onto the take-up spool. The instruments were very successful for the particular purpose, and could be adapted to the present requirements by 1) using a larger aperture to give an adequate sample (only small ranges of drop sizes occur in Hawaii), 2) a much faster tape speed (even medium

instead of time-operated triggering mechanism.

However, in spite of many successful applications of the paper-stain technique, it was not considered the most suitable for the present experiments for two main reasons:

- 1) The standards of accuracy are adequate for meteorological studies of the general nature of drop distribution as expressed by, for example, median drop diameter, or where the distribution is to be related to inexactly measured, or non-concurrent, characteristics such as radar echo or average intensity. In such cases the misallocation of one size group of drops into the adjacent group will not materially affect the result, but when, as in the present case, the study includes kinetic energy, which involves the squared power of velocity, then the drop size and hence velocity must be determined as accurately as possible. Neuberger (51) estimated that, owing mainly to the fact that a large number of drop stains are deformed by splash effects, the error in the estimation of mass by this method of measurement may be as high as 14%.
- 2) The mechanical problems of designing a suitable recording instrument could certainly be overcome but since the use of a flying spot scanner is financially impossible in the present case, the 'by hand' measurement of a vast number of drop stains would be a very real problem.

All the possible methods so far considered have thus been eliminated as unsuitable for one or more reasons and it remains to discuss the remaining method, which is suitable, and was used in the present experiments.

4.4.8. The Pellet Method.

Instead of catching the raindrops in oil or on absorbent paper they may be caught in a powder with which water combines to form solid particles. Suitable powders are cement, household flour, and plaster of paris. Provided an exact relation can be established between the size (or mass) of a pellet and the size (or mass) of a drop which will form such a pellet, then the size and size distribution of raindrops can be calculated from that of pellets formed by a sample of rain. Of the powders mentioned, neither cement nor plaster of paris are very suitable as the moisture of an individual drop tends to spread into the surrounding powder, but flour forms a discrete pellet which after oven drying becomes hard and capable of withstanding mechanical handling and sorting. The flour is placed in a shallow dish or tray, and exposed to the rain for an interval of time consistent with catching an adequate number of drops without there being so many that some drops land on top of the pellet formed by a previous drop. Sorting of the oven dried pellets

can be done by passing them through a nest of sieves with progressively smaller apertures, and the number of groups is limited only by the number of sieves used. From the weight of pellets in any one size group it is possible to calculate the total weight or number of drops falling within the corresponding size limits.

The method was first used by Bentley (118) in 1904 to measure drop sizes in natural rain, and a number of subsequent research workers have improved on his technique and used it for various purposes. Laws (39) and Blanchard (66) measured the size of drops whose velocity was being measured in the laboratory, and Laws later (119) extended this to studies of natural rain using similar techniques. Schleusener (120) studied the effects of nozzle design and pressure on the spray patterns of irrigation sprinklers, Meyer (121) tested artificial rainfall simulators, and Chapman (122) compared the erosive effects of rainfall under a tree canopy and in the open. Studies of the size distribution of natural rain have also been made by Blanchard (123) and Ker (22).

The main disadvantage associated in the past with this technique has been the lack of accuracy in calibrating the relation between the mass of a flour pellet and the mass of the drop which forms a pellet of this mass. This is subjected to detailed study in the following chapter, and the probable sources of error in the previous studies are identified and eliminated. The design of a machine to allow automatic sampling of rainfall by this method, and the operational procedure for handling the samples are described in Chapter 8.

4.5. KINETIC ENERGY OR MOMENTUM.

An association between erosion and kinetic energy can be deduced from the fact that erosion is a work process involving the expenditure of energy in carrying out the several processes, viz. the disruption or breaking down of soil particles or aggregates, the splashing of soil particles into the air, and the transportation of soil particles. The available sources of energy are kinetic energy from the falling rain, and both potential and kinetic energy of water flowing over the ground surface. The energy of falling rain is usually far greater than that of surface flow. The rain arriving at the soil surface has an average velocity of about 20 - 30 feet per second, whereas the run-off is only a portion of the total rain and has a lower velocity. There are exceptions to this when the run-off from a larger area is concentrated onto a smaller area, or on long slopes where potential energy is transformed to kinetic energy during run-off, but in cases such as arable lands the energy of the rain is several orders of magnitude greater than the energy of run-off. It is probable, then, that Kinetic energy is an important feature of erosive power.

The question of whether momentum or energy serves as a better measure of erosive power will be considered later. As both are functions of a combination of mass and velocity, either can be computed from measurements of these two variables which were discussed earlier in this chapter. Direct measurements of both energy and momentum will be discussed in Chapter 7.

University of Cape Town

CHAPTER 5.

CALIBRATION OF THE FLOUR PELLET METHOD.

5.1. CONTROL CONDITIONS REQUIRED FOR CALIBRATION.

Having arrived in the previous chapter at the conclusion that the flour pellet method is the most suitable technique for the present investigations, it is now considered in detail. Obviously any results of rain drop sizes depend directly upon the relationship between the size (or mass) of the drop and the size (or mass) of the flour pellet, and this relationship must first be established by a laboratory calibration. A number of previous calibrations have been carried out, but the accuracy of all of them is doubtful as the necessary control conditions were not applied. Before analysing the present calibrations, and presenting a new and more accurate one, it is appropriate to consider the effects of these controls. Some are required to ensure that the laboratory calibration is accurate, others to ensure that it may be applied without error to field observations. For example the weight of the pellets depends upon how much they are dried. Provided the same method is used in the laboratory and in the field, errors are not necessarily introduced, although complete drying to constant weight is the most precise method. On the other hand if the laboratory calibration uses drops falling into the flour at a lower speed than that of natural raindrops, and if, as will be shown later, the pellet mass is influenced by this speed, then an error will inevitably be introduced when the laboratory calibration is applied to field samples.

5.1.1. Methods of Producing Water Drops.

The calibration consists of allowing drops of known size to fall into flour and determining the size of the resultant pellet. This must be repeated at several points in the range of natural rain drop sizes to be studied, which is from 0.1 mgm. to 50 mgm. Many measurements are required at each size, so uniform drops of constant size are necessary. A suitable method is to allow water to drip from nozzles whose rate of flow can be very finely controlled and

adjusted by suitable valves, or by clamps on flexible tubing. The nozzles may be turned from brass tubing, glass tubing drawn out to suitable sizes, or hypodermic needles. Owing to surface tension effects, drops of the smallest sizes required will not detach themselves by gravity alone, but these may be blown off by an air stream. Gunn and Kinzer (40) showed that using a co-axial air stream directed vertically downwards it is possible to produce drops of a mass ranging from 0.25 to 10,000 micrograms using a single hypodermic needle by varying the rate of water flow, and the speed of the air stream. The method was also used successfully by Rasbash (124) to produce sprays of small and constant droplet size in connexion with fire-fighting research. Meyer (121) suggests that a slight horizontal component of velocity of the air stream is desirable to avoid the air blowing directly into the vessel used for catching the drops, and in the present calibration this practice was adopted, although it was done for a different reason discussed later. Lane (125) developed a micro-burette also using a hypodermic needle and co-axial air stream for producing very small drops whose mean size can be determined with great accuracy, but even so the variation of individual drop diameter was approximately 3% of the mean. This apparatus was improved by Levvy (126) to produce drops more slowly, but the standard deviation of drop mass was 2% for 0.6 mgm. drops, and 10% for 0.125 mgm. drops. Alternative methods of drop formation include throwing off drops from the edge of a rapidly spinning disc (Yates 127), and the use of a rapidly vibrating blade to cut off droplets from a column of water (Amsden 128; and Magarvey and Taylor 129). Blanchard (130) used the ingenious method of blowing, through water, air bubbles which on bursting at the water surface project very small droplets into the air, and was able by this means to make droplets down to 2 microns diameter. Although drops of this size may occur in natural rain their volume is insignificant. The lower limit at which the volume does become significant, and at which it is possible to isolate the resultant pellet is about 0.1 mgm. Difficulties met by early workers trying to produce drops of this size fall away when the use of an air stream is adopted.

The apparatus used in the present experiments is shown in Plate 5.1. and with different combinations of nozzle and air stream gave drops of sizes throughout the required range. Meyer (121) also suggests that to avoid evaporation during the formation of the drop, the air should be saturated by passing it through several flasks of water. It is not possible to test this as to switch from saturated to unsaturated air involves changes in the air velocity, and the slightest change in any of the conditions of drop formation results



Plate 5.1. Drop Producing Apparatus.

The flow of water to the hypodermic needle is controlled by the stop cock and screw clamp on the left. The air stream from the glass tube is controlled by the air valve at the top centre.

in a change of average drop mass. However, the object is not to produce drops of a particular size, but to produce drops as uniformly as possible of any suitable size. Using a non-coaxial air stream the humidity of the air stream will only influence evaporation during formation (when it is irrelevant) and for the fraction of a second after detachment before it passes through the air stream into free fall through the general mass of unblown air in the laboratory. The effect of evaporation during the period of fall is discussed later. Harkins and Humphery (131) showed that very accurate or turned nozzles with sharp edges are required to minimise drop variation, and Morgan (132) emphasised the importance of all control conditions, particularly temperature, and freedom from both vibration and grease contamination. In the present studies the larger drops were formed from turned brass nozzles, and the smaller from various sizes of hypodermic needles whose ends were carefully ground to a flat surface at right angles to the length of the needle, and the inside burr removed. Distilled water was used, supplied from a tank whose surface area is large enough that there will be a negligible change of head during the experiment. Once a particular test has started, the rate of water supply, and the air supply, must remain absolutely constant because, as will be shown later, the drop mass is dependent upon the rate of formation, and the whole apparatus is best not touched at all during tests on a particular drop size. It was found that even under these conditions there was always a tendency for the rate of formation to decrease slightly. A possible explanation is that minute impurities in the distilled water exercise a progressive choking effect at the taps and clamps controlling the water supply, and so once a particular and suitable drop size is being produced the test must be completed as quickly as possible, with constant checking by stop-watch of the rate of drop production. Changes of temperature, which might affect the viscosity or surface temperature of the water, should also be avoided. The actual moment of partition is not solely dependent upon a simple equating of gravitational force to surface tension forces, but is also influenced by vibrations and oscillations of the forming drop (as will be discussed later), so the drop producing apparatus must be free from vibration. Particularly if, as in the present studies, a high speed centrifugal pump is used to produce the air pressure it must be supported independently, preferably in a different room.

5.1.2. Measurement of Drops.

In all methods of drop formation which have been discussed, there is some variation in the mass of individual drops, and it is

essential not only to measure the drops as accurately as possible, but also, a point which has been inadequately covered in previous investigations, to estimate the magnitude of this variation. The difficulties in measuring the size of raindrops, discussed in the previous chapter, apply equally well to water drops in the laboratory, and the two possible methods offering sufficient accuracy are direct weighing of drops, and the measurement under a microscope of the diameter of drops immersed in oil. Tate and Marshall (50) studying the size distribution of very small droplets formed from high pressure centrifugal nozzles, caught the drops in brass cells with a glass bottom and containing "Stoddard's solvent". This fluid was chosen as it has the property of not absorbing any of the water droplets, and a specific gravity so near to that of water that the drops rest lightly on the glass bottom with no deformation from a truly spherical shape. The drops were photographed through the glass bottom, and the drop diameters measured from enlargements of the photographs. Gunn and Kinzer (40) used a variation of this method, catching the drops in a shallow dish of high quality vacuum pump oil, and measuring the drop diameter directly under a medium-power measuring microscope. They state that this method is accurate "to better than 2 percent for droplets of mass 10 micrograms and less than 0.5 per cent for droplets of 10,000 micrograms" but do not show how these figures were calculated. To allow for deformation of large drops, a total reflecting prism immersed in the oil was used to measure the vertical diameter in addition to the horizontal diameter.

The alternative method of direct weighing has the advantage of simplicity, and should be more accurate since volume measurements depend upon the cube of the measured diameter. Gunn and Kinzer in the same study used direct weighing for the larger drops but found it impracticable to weigh the smaller droplets. Presumably this was because of the minute size, as drops of mass 0.25 micrograms must be barely visible to the naked eye. In the present investigations direct weighing of drops down to 0.08 mgm. was found to be both practical and accurate, but this is approaching the point at which weighing errors would become of consequence. Groups of drops were caught in shallow dishes containing about 0.5 cm. depth of S.A.E. 20 motor oil and weighed on a sensitive balance weighing to the nearest .05 milligrams. For the smallest drops studied (0.08 mgm.), when weighed in groups of twenty drops, the maximum weighing error is about $1\frac{1}{2}\%$, but this decreases as the drop mass increases. These smallest drops were included to confirm the trend of the drop mass/pellet mass relationship beyond the range in which it will

actually be applied. The lowest drop mass at which the relationship is used will later be found to be 0.17 mgm., and at this level the maximum weighing error is 0.75%.

Evaporation losses from the drops during the period of collecting and weighing are significant. The loss can be reduced by using tared containers with lids which are closed immediately after collection, but collection directly into oil is both simpler and more accurate. This method also has the advantage that the individual drops can be counted in oil to ensure that the correct number have in fact been caught. The smallest drops formed with a high ^{air} pressure leave the dropping point so fast that their path and point of impact in the collecting dish cannot always be followed by eye. If a drop missed the collecting dish this would be detected in the weighing, but there is always the possibility that a drop might strike the edge of the container and a portion of the drop be lost in splash, so a visual check of the number of drops is useful.

Changes in weight of the tared vessel containing oil are only significant after about three hours, and as each test was carried out in a matter of minutes no error was introduced. Absorption of some of the water drops into the oil also takes place slowly, and it is irrelevant since it does not affect the weight. Naturally extreme care is required in the handling of the containers, placing them only on clean dry surfaces, and covering them to avoid dust.

In considering the number of drops of each size to be caught and weighed, a balance must be struck between two incompatible requirements. The largest practical number of determinations is desirable for accurate estimation of drop size variation, but the test must be completed as quickly as possible to minimise the risk of progressive variation with time of the average drop mass. The co-efficient of variation of individual drops was found to decrease as drop mass increases (Fig. 5.1.) and so for comparable estimations of the mass of the drops a larger sample is required for the smaller drops. In the final tests, groups of ten drops (and ten flour pellets) were used for the larger drops, and groups of twenty for the smaller drops and pellets. It is physically impossible to use the same drop or group of drops both for a measure of drop mass and the pellet mass so a sequential procedure was followed. Once an apparently stable rate of drop formation was achieved a group of ten (or twenty as the case may be) drops was caught in oil, the next ten caught in the flour pans, the next ten in oil and so on for four groups of drops and four groups of pellets. A few drops are lost during the changeover from collecting the drops in oil and catching them as

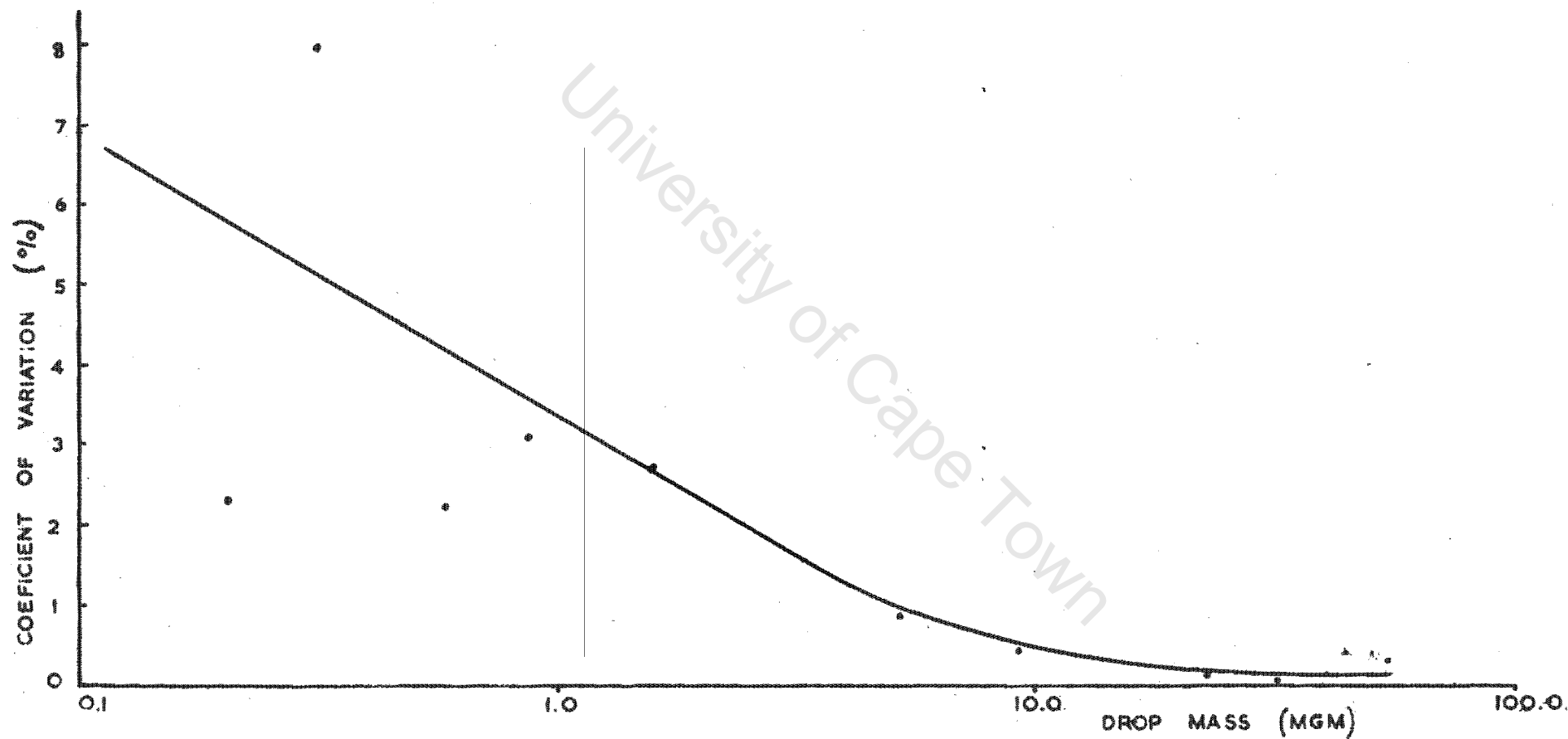


FIG. 5.1. VARIATION OF AVERAGE DROP SIZE IN GROUPS OF 20 DROPS.

pellets, but by using previously prepared flour pans and tared collecting dishes for the drops, this was reduced to a minimum and the whole sequence completed in a few minutes. A significance test was used to detect any progressive variation in the groups and any test showing a positive variation with time was discarded. The reasons for this are discussed later in section 5.1.4.

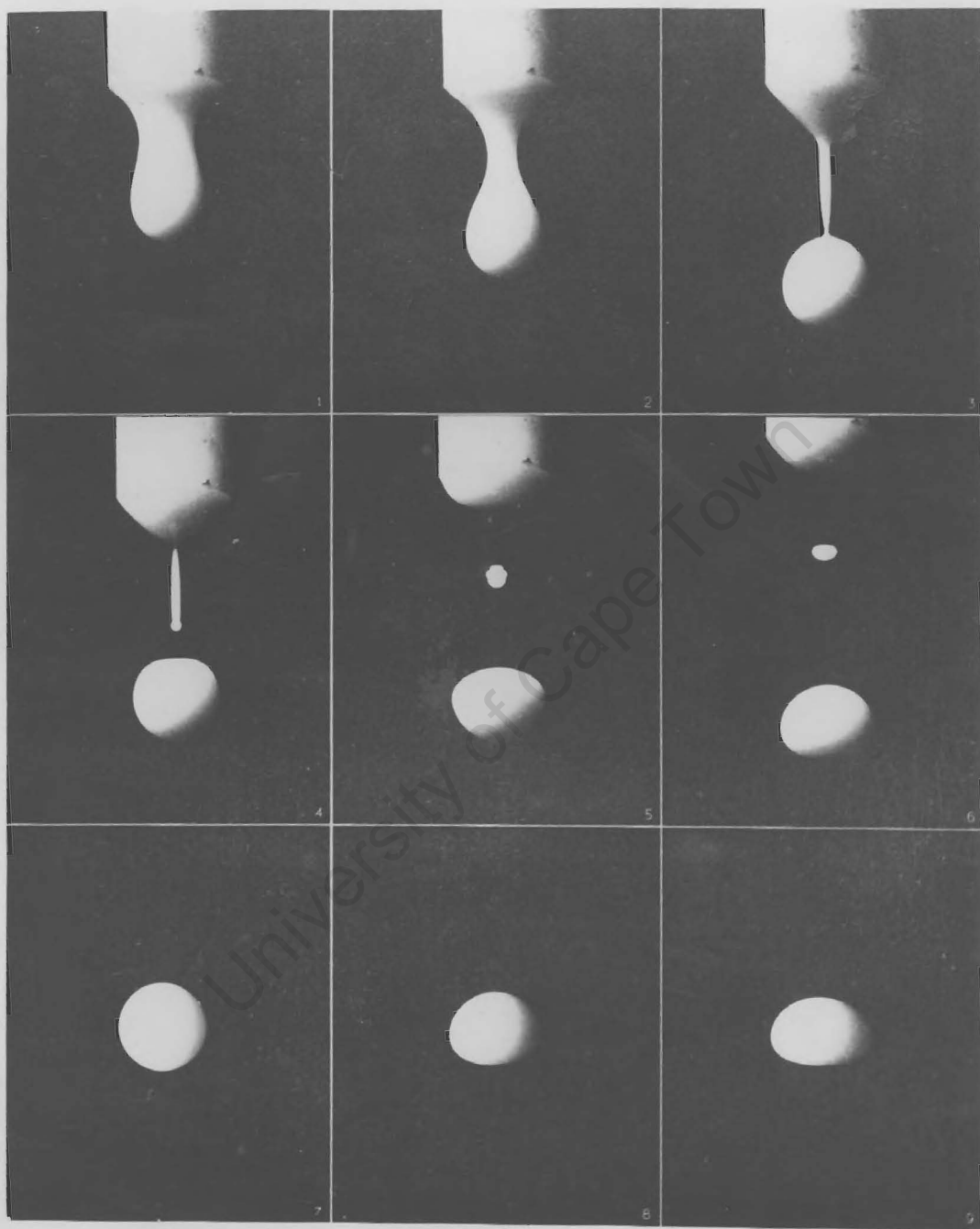
It is unfortunately impracticable to catch both the drops and pellets at the same height below the dropping point. It will be shown later that the drops must strike the flour at nearly terminal velocity, which requires a height of fall of nearly 30 feet for the largest drops. The point of impact after such a fall is by no means constant, especially with small drops, as eddy currents and drop oscillations make the flight path vary. A large pan of flour can be used to catch the pellets, but for sensitivity of weighing the size of the vessel used for catching the drops is limited, and so the drops must be caught at the beginning of the fall, a few inches below the dropping point. Another reason for not collecting the drops at the bottom of the fall is the difficulty of catching the drops without splash. Attempts to catch the drops in conical containers, and in flour, cotton wool, various oils, etc., showed that errors due to splash, either of the drop or the collecting medium, could not be avoided. It is interesting that a drop falling onto a clean, dry, smooth, surface such as glass does not splash upwards but merely spreads radially. This was observed by Gold (133) and Worthington (134 and 135), but does not offer a solution as the evaporation loss would be serious. The effect of evaporation during fall will be considered later in section 5.1.6.

5.1.3. The Mechanics of Drop Formation.

Since early in the last century the mechanics of drop formation at an orifice or nozzle have been extensively studied, chiefly by chemists and physicists interested in determinations of the surface tension of liquids, and later by bacteriologists or pathologists interested in producing accurate drops of known size. In early studies the surface tension was determined by equating the weight of the drop, as measured by weighing after separation, to the surface tension effects at the maximum wetted periphery of the nozzle during drop formation. Results which differed considerably from those obtained by other methods led to the observation by Guthrie (136) in 1963 that a secondary or "satellite" drop is formed at the moment of separation, and he suggested that the

satellite drop was ejected upwards from the main drop by violent oscillations immediately after separation. Worthington (137) in 1881 pursued this, and observed that the secondary drop is formed from the extended neck which forms just before complete separation. Guye and Perrot (138) in 1903 recorded the stages of drop formation photographically. All these earlier workers observed visible oscillations of the pendent drop. The exact processes of formation were clearly and finally resolved when modern techniques of high speed photography were used, particularly by Edgerton (62 and 139). Hauser and Edgerton (140) give this account - "The actual mechanism of fall is very complex. The drop grows larger and larger at the end of the dropping tip; then instability sets in, and a large part of the drop breaks off, leaving a narrow stem attached to the remainder of the drop. At the moment of break-off the drop is nearly spherical. The narrow neck then breaks off from the main body and constricts to form one or more droplets". Using liquids like nitro-benzene several discrete droplets may form from the neck, but water coalesces into a single drop. However, it is interesting that Guthrie's observation on the upward movement of a satellite drop was very close to the truth, which is that the secondary drop oscillates so violently that it sometimes ejects upwards a still smaller tertiary drop. This tertiary drop is occasionally projected high enough to rejoin the water remaining on the dropping tip. Plate 5.2. reproduced from Edgerton's book, shows the formation of the main and secondary drops.

This study of the mechanics of drop formation arose from the writer's observation of the secondary drop, which appears to the naked eye to detach itself from the main drop after a fall distance of a foot or so. In this calibration exercise it may lead to error because if the collection vessel is held a few inches below the dropping point the secondary drop will also be caught, but the secondary pellet will not be noticed in the flour. It is not clear from Hauser's work whether this secondary drop is produced during the formation of drops of all sizes, or only when large drops are formed. Laws (39) implies that it only occurs with drops of 6 mm. diameter, but this may be due to the fact observed by the writer that it is only with such large drops that the secondary drop is visible to the naked eye. As to the magnitude of the secondary drop, Laws estimated it roughly from photographic images as "less than one percent" (for 6 mm. diameter drops). Hauser (140) states that it was found to be 3.12% but does not indicate the size of the main drop when this was determined. Kelkar (141) refers to the secondary drop as Plateau's spherule, and used it as a source of small droplets, but found that the ratio of the sizes of the main and secondary drops



FORMATION OF A DROP. II

A small drop follows the larger and during its oscillations takes the unexpected shape revealed in 5. Picture 8 shows a drop that has fallen six or eight feet. During this fall the oscillations have ceased, and the forces of windage and surface tension gradually reach a balance, resulting in the stable shape shown. The drop in 9 has fallen 14 feet and flattened slightly but has the same contour as the drop in 8

Plate 5.2. The Process of Drop Formation.
(Reproduced from "Flash" by Edgerton and Killian)

"undergoes erratic fluctuations". In the present experiments estimates made using ^{the} filter paper technique suggest that the secondary drop had a mass of 1 or 2% of the main drop.

The actual magnitude is not important. It is an error, and as such must be eliminated if possible. This can be achieved quite easily by directing a gentle air stream downwards and slightly sideways so that the small secondary drop is deflected slightly more than the main drop. The collecting dish is then held at a point about 6 inches below the dropping point in such a position that the main drop is caught, but not the secondary drop. To check that the secondary drop has missed the collecting dish it is caught on dye-treated filter paper held alongside the collecting dish. Not knowing whether the secondary drops also form with medium and small drops, the technique was used for all drops. For the large drops where the air stream is not required to assist the drop detachment, the air stream nozzle was mounted 2 inches below and slightly to one side of the dropping point; for the small drops the faster air stream used to detach the drops was given a sideways inclination to deflect any secondary drops, (Plate 5.1.).

5.1.4. The Effect of Rate of Formation Upon Drop Mass.

Early in the present studies it was observed that on different occasions the average drop size produced from a particular nozzle varied considerably from test to test under apparently identical conditions. Eventually it was found that this variation was in fact due to small changes in the rate of formation of the drops, and that a regular relation obtains between drop size and rate of drop formation. A literature search revealed that this was no new phenomenon, but had been extensively explored in the past.

The earliest studies of Guthrie and Worthington refer to this effect. Since air pressure was not used in these investigations the drops were presumably large and it was found that the drop mass decreased as the time to form increased. Hauser (140) reports the same effect, but does not give any data. Donald (142) and Fildes and Smart (143) studied this phenomenon in connexion with the production of uniform drops for medical tests, and portions of their data are shown in Figs. 5.2. and 5.3. Donald is the only known investigator reporting on the behaviour of small drops and his result confirms that of the writer that for small drops the effect is reversed - that is small drops increase as the time to form increases. Fildes and Smart criticise Donald's inference that for small drops the mass becomes almost constant at formation rates slower than one per

second. (Fig. 5.3.). This criticism is unfounded since their own data (Fildes and Smart's) are only for very large drops. Fig. 5.4. combines the data of Figs. 5.2. and 5.3. to show that the minimum time of formation for constant drop size does decrease as the drop size decreases, and as Donald quite rightly said it is about one second for drops of 5 mgm. Lacking evidence, there is no justification for extrapolating beyond this to very small drops. It is, however, most unlikely that the trend would be reversed for very small drops, and the assumption was made in the present investigations that the minimum time of formation should be one second for all drops up to 5 mgm., and for larger drops the minimum time should be not less than the appropriate value from Fig. 5.4. As a further check the total time of formation for each group of drops was measured and when this varied appreciably the drops and pellets were discarded.

The reasons for this phenomenon of drop mass varying with time of formation, and the fact that the effect is in opposite directions for large and small drops, were pursued in case such study might suggest ways of making more accurate and predictable drops. Worthington (137) suggested that it might be due to an influx of water through the narrow neck of the pendent drop about to fall, and velocity effects of this water. The writer considered the possibility of the frequency of oscillation of the pendent drop interacting with the time of formation. No reported values are known for the frequency of vibration of the pendent drop, although this vibration can be clearly seen in the large drops, but values are available for the falling drop. Rayleigh (144) derived a semi-empirical formula, and Blanchard (66) measured the frequency experimentally.

Both approaches give values for the frequency of 60 mgm. drops (the largest with which we are concerned) of about 30 to 40 cycles per second. There is no certainty that the pendent drop has the same frequency of vibration, but it is certain from observation that the vibration is very rapid, and it is difficult to see how such a period of vibration can interact with the period of formation, which differs by one and probably two orders of magnitude.

Worthington suggested (137) that velocity effects of the "last minute" influx of water through the elongated neck influence the moment of separation. It is conceivable that some such effect combines with gravitational forces in such a way as to give a net result which is opposite in sign for large and for small drops, but this is pure conjecture and does not appear to lead constructively towards improvement of the method of making uniform drops. What is

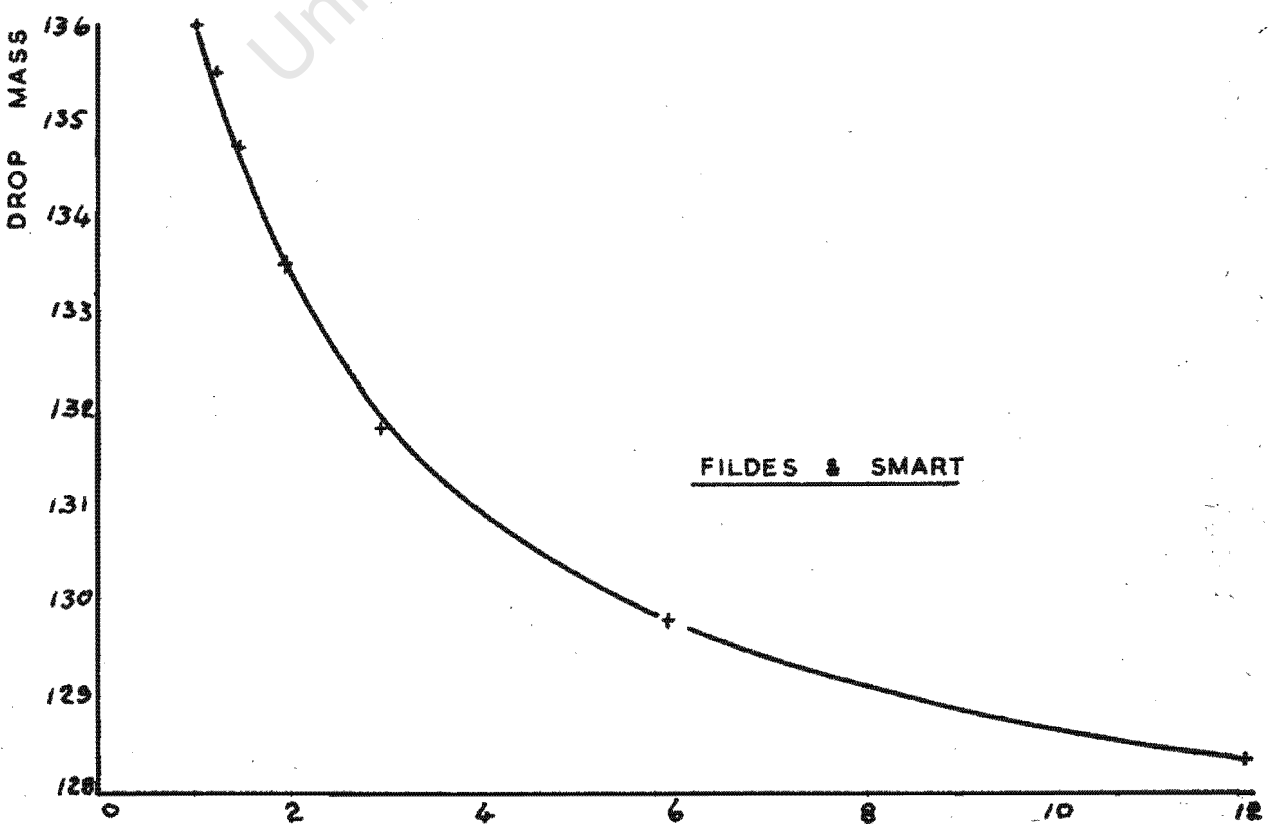
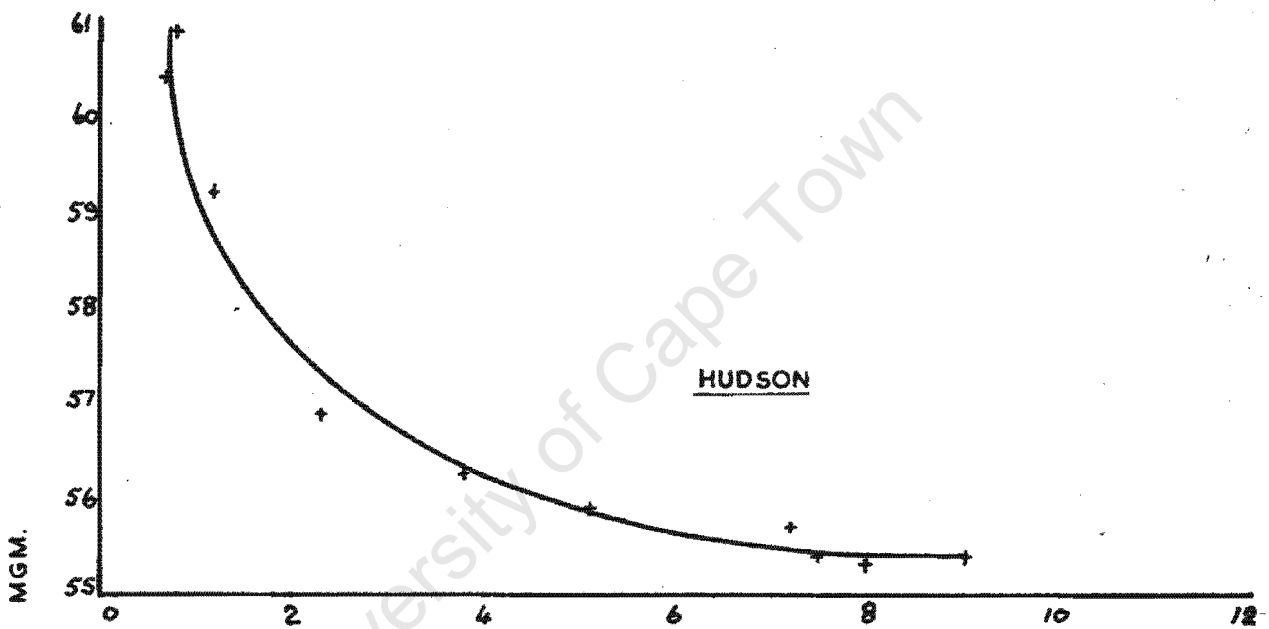
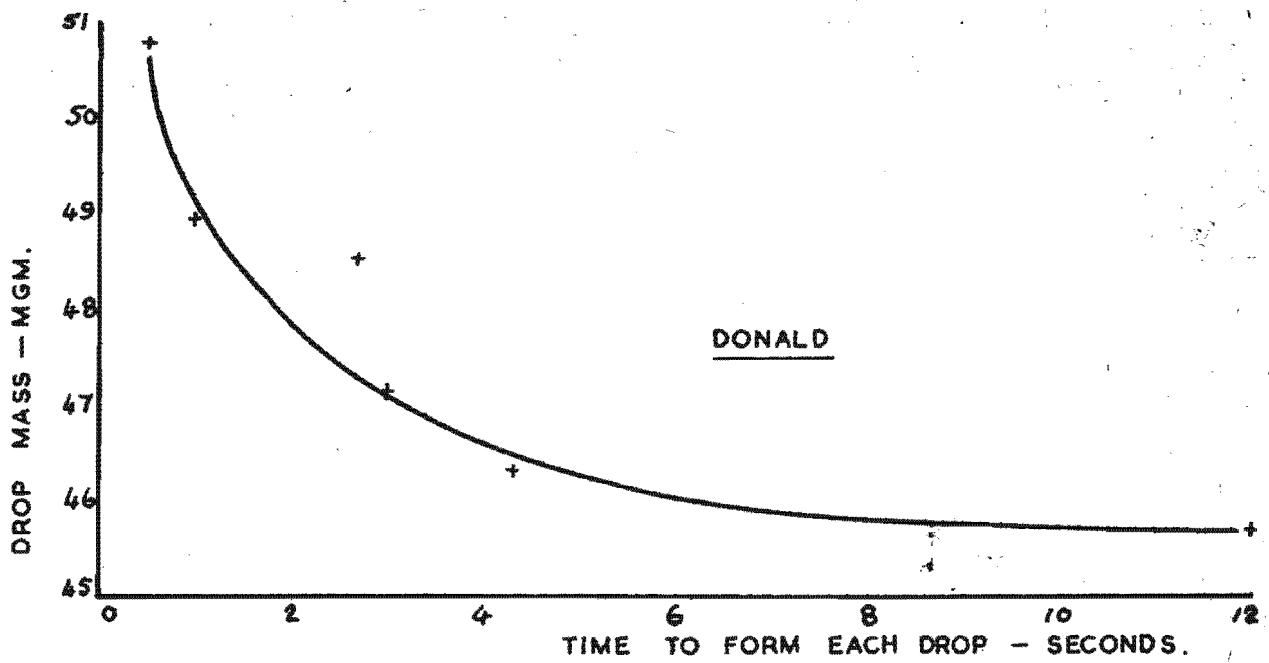


FIG. 5.2. VARIATION OF DROP MASS WITH CHANGE IN TIME OF FORMATION.

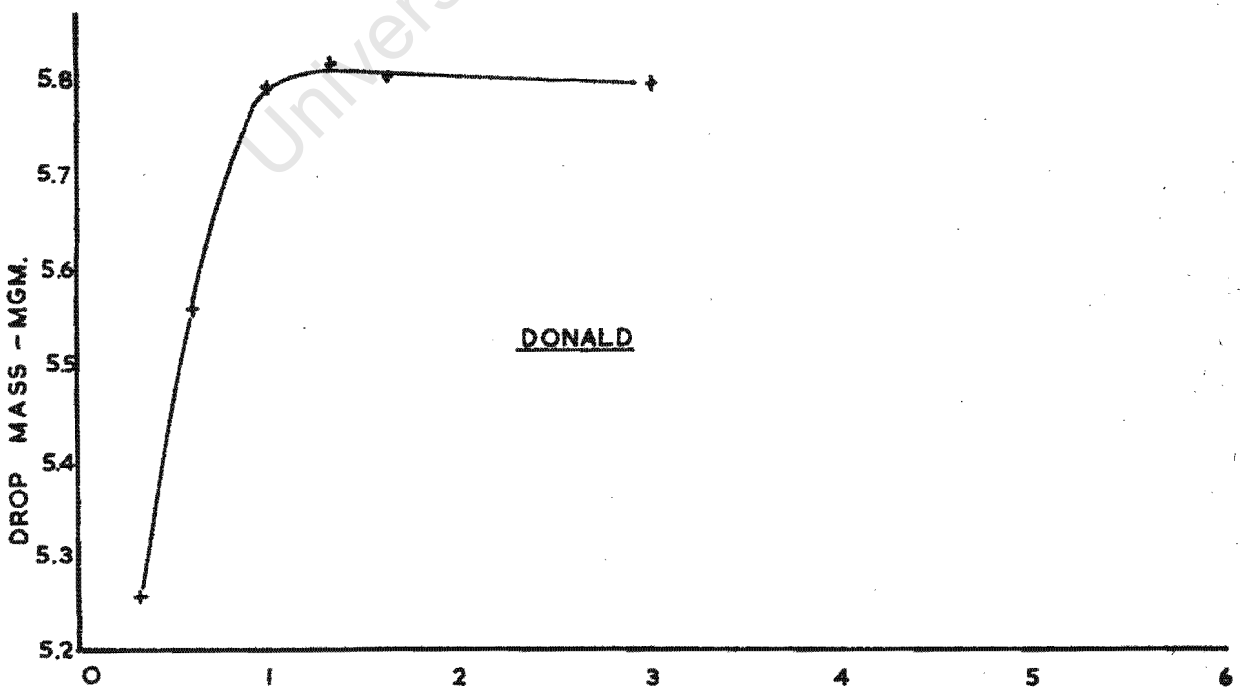
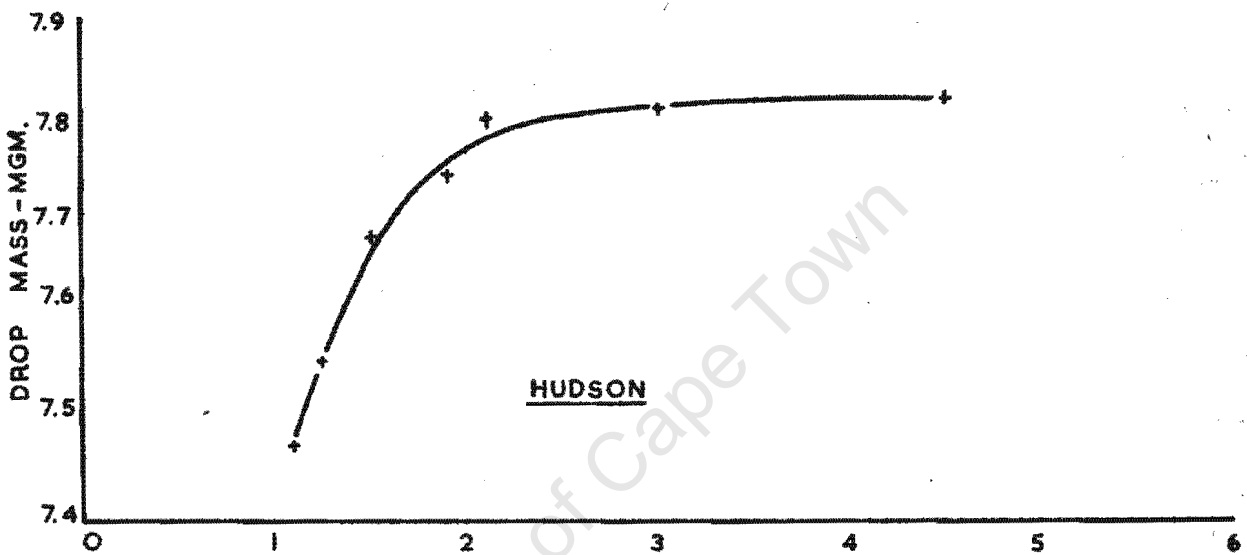
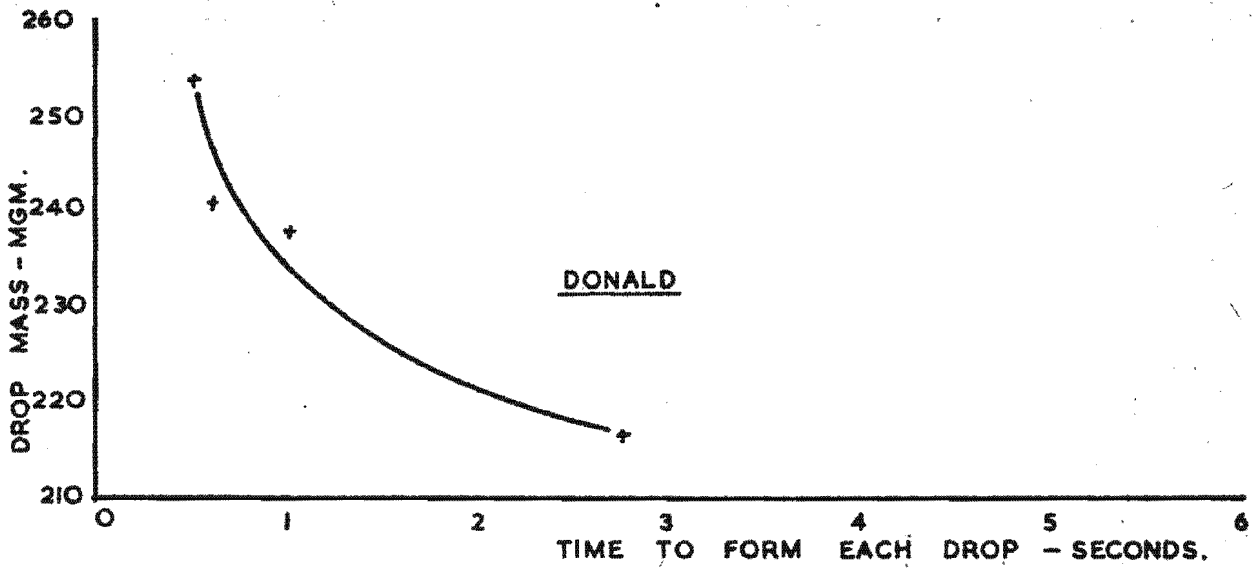


FIG. 5.3. VARIATION OF DROP MASS WITH CHANGE IN TIME OF FORMATION.

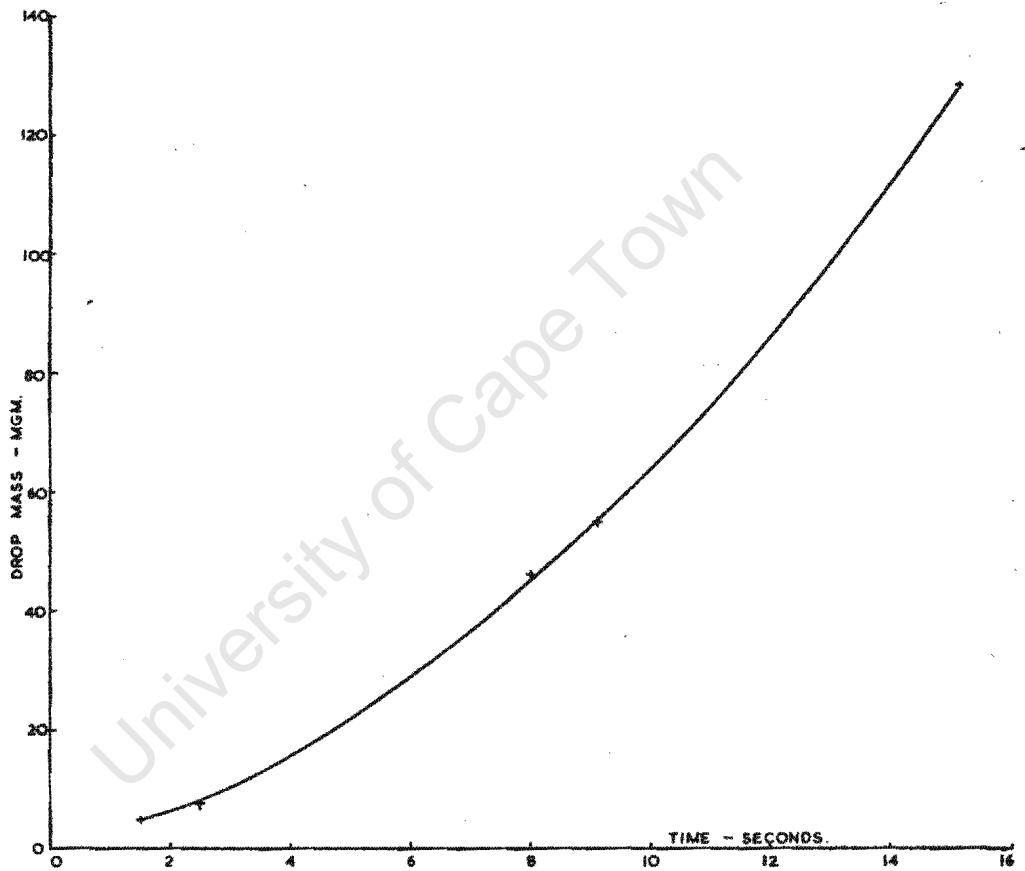


FIG. 5.4. LEAST TIME OF FORMATION REQUIRED FOR PRODUCTION OF DROPS OF UNIFORM SIZE.

relevant is that the failure to pay due regard to the necessity of constant time of drop formation may have led to appreciable errors in some of the earlier calibrations.

5.1.5. Range of Drop Sizes Required.

In order to avoid the dangers of extrapolation, when applying the calibration curve to flour pellet samples obtained in field experiments, it is important that the calibration should cover the whole of the expected range.

The upper limit of drop size required is the maximum drop anticipated in natural rain. Reported values, and estimated values, vary considerably. Blanchard (66) found that drops supported in an upward current of air were stable up to sizes of 4.6 mm. (approximately 50 mgm.) and definitely unstable above 5.4. mm. (approximately 85 mgm.), with a transition zone between where the stability depended upon the degree of fluctuations in the air stream. Lenard (46) reports drops of 5.2 mm. in natural rain, and Weisner (97) reports a normal maximum of 5.3. mm. with very exceptional drops up to 6.7 mm., but unstable drops can occur in natural rain due to coalescence short distances above ground level. In fact it will be shown later that the relationship between drop mass and pellet mass becomes almost constant at drop sizes above about 4.0 mm. diameter (35 mgm.). An upper limit of about 4.6 mm. therefore restricts the calibration to stable drops, but permits extrapolation to slightly larger sizes with reasonable confidence.

With small drops, however, the departure from a linear relationship between drop mass and pellet mass increases as size diminishes. Chosen values for drop mass are required to have even distribution on a logarithmic scale in order to study this relationship, and the smallest drop should correspond to that of the smallest of the size groups into which it is intended to sort the natural rain samples. It is impracticable to sieve, sort, and weigh, the pellets from natural rain into size groups with a mean mass less than about 0.2 mgm. and so that lower limit required in the calibration is the corresponding drop mass of about 0.16 mgm.

In the present investigations the calibration was extended down to drops of a mass 0.08 mgm., the smallest obtainable with the apparatus already described, in an attempt to understand better the nature of the relationship between drop mass and pellet mass.

5.1.6. Evaporation Effects.

The question must be considered of whether evaporation causes a significant change in the mass of the drops between the point of collection and point of pellet formation. The losses are certainly small and are not detectable by direct weighing because, as explained earlier, it is not possible to weigh with sufficient accuracy drops caught after a fall of several metres. The problem has, however, been investigated elsewhere, and a computation of the weight loss is possible. Namekawa and Takahashi (145) give an equation empirically obtained from experimental data using velocities up to 2 metres/second only. There is little justification for extrapolating to terminal velocities of the order of 9 metres/second, but doing so to obtain a first estimate of the order of the loss, we find that the loss of weight of a drop of mass 33.51 mgm. is .005 mgm. during a fall through 8 metres, and this is not significant.

Kinzer and Gunn (146) used much more accurate methods to measure evaporation losses over a wide range of conditions. Their results are presented in the form of two evaporation factors, one dependent on the drop size and air temperature, the second dependent on the temperature and relative humidity of the ambient air. The product of the two factors gives the loss in weight per unit time. The values for the drop sizes, heights of fall, and air conditions used in the present investigations are tabulated in Table 5.1. The time of fall has been calculated from the data of Laws (39) who measured the velocity at various heights of fall. The evaporation loss was kept as low as possible by carrying out the calibration on days when air conditions were favourable. The error decreases as drop size increases, ranging from 0.72 to 0.1%, and no correction was made for this small effect, but in hot dry air the loss could be three times greater and this would require correction.

5.1.7. Measurement of Flour Pellets.

Variations in the shape of the flour pellets preclude measurement other than by weighing, and, as with the drops, it is necessary not only to measure the mean pellet mass but also to estimate the variation about this mean. This was done in the same way as for the drops, that is by weighing 4 groups of 10 large pellets and 20 small pellets. It might be expected that the pellet variation would be greater than the drop variation, because the pellet variation includes the variation in drop size and also variation due to flour effects. However, the pellet variation shown in Fig. 5.5. is similar to the drop variation (Fig. 5.1.) except that it is less dependent on

TABLE 5.1.

EVAPORATION LOSS FROM WATER DROPS DURING FALL.

Drop No.	Ht. of Fall (Metres)	Drop Mass (mgm)	Drop Diameter (m.m.)	Temp. (°C)	Relative Humidity (%)	Evaporation Factor A (from Kinzer and Gunn 146)	Evaporation Factor B	Evaporation Product (10^{-3} mgm/sec.)	Time of Fall (secs.)	Total Evaporation loss during Fall mgm $\times 10^{-3}$	Loss as % of Drop Wt.
1	2.29	0.0800	0.539	21.7	58	1.085	0.718	0.779	0.74	0.58	0.72
2	2.29	0.2038	0.730	18.3	64	1.725	0.755	1.302	0.73	0.95	0.47
3	3.73	0.3117	0.840	21.1	57	2.135	0.710	1.516	1.09	1.65	0.53
4	3.73	0.5787	1.034	21.1	57	2.93	0.710	2.080	1.05	2.18	0.38
5	3.73	0.8587	1.180	21.1	57	3.60	0.710	2.556	1.02	2.61	0.30
6	3.73	1.567	1.440	18.3	64	4.93	0.755	3.722	0.97	3.61	0.23
7	3.73	2.383	1.656	21.7	58	5.95	0.718	4.272	0.93	3.97	0.17
8	6.86	5.208	2.15	13.3	69	9.64	0.55	5.302	1.40	7.42	0.14
9	7.65	9.235	2.60	19.2	44	13.84	0.86	11.902	1.40	16.66	0.18
10	7.65	23.055	3.53	19.2	44	26.80	0.86	23.048	1.33	30.65	0.13
11	7.65	33.930	4.02	19.4	37	36.0	0.985	35.46	1.31	46.45	0.14
12	7.65	55.510	4.74	19.2	44	49.0	0.86	42.14	1.28	53.94	0.10

pellet size. The sampling method used for the drops is therefore also suitable for the pellets.

5.1.8. Relationship between Drop Mass and Pellet Mass - Mass Ratio.

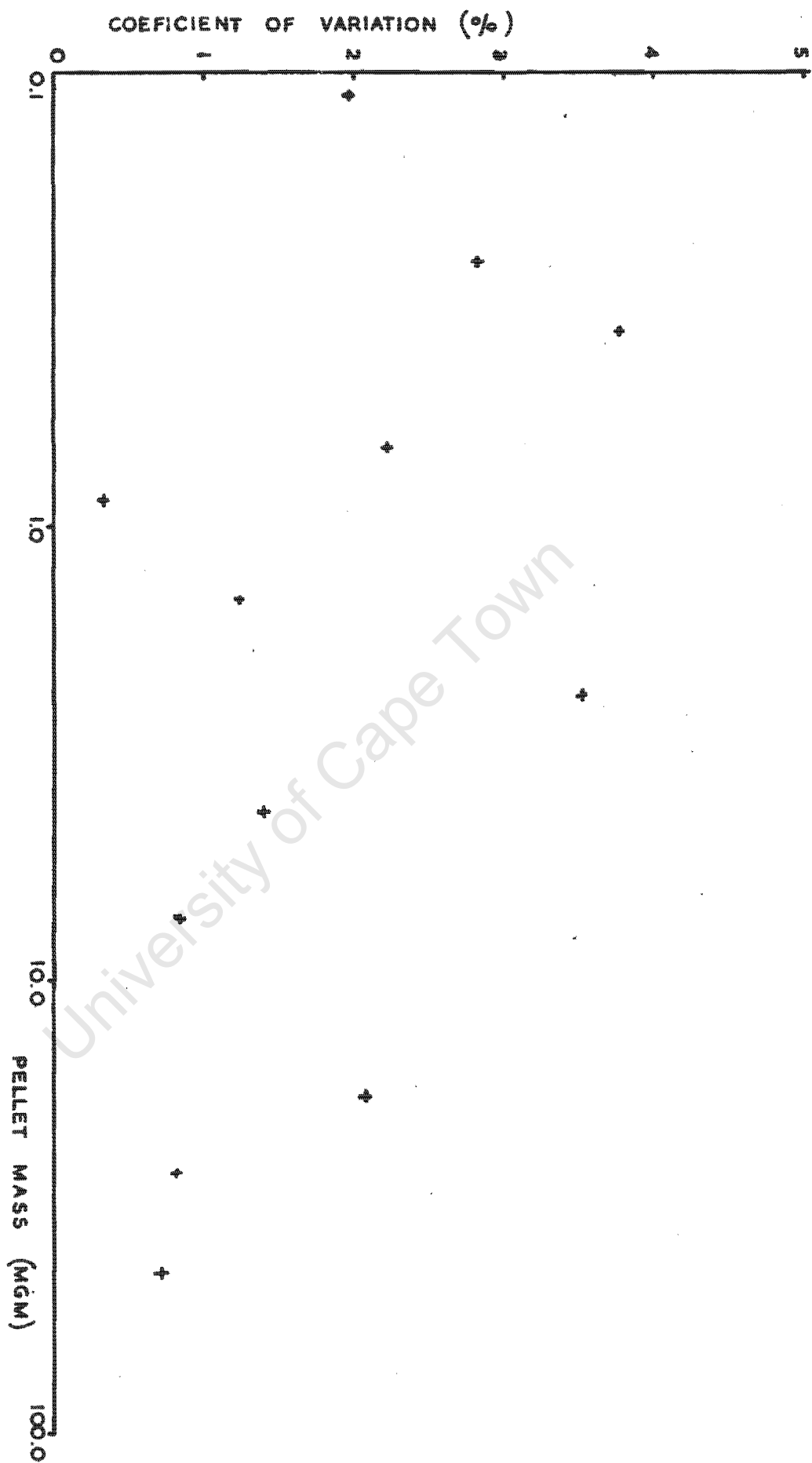
Laws (39) coined the term "mass ratio" for the factor drop mass divided by pellet mass, and this is a useful way of expressing the relationship both in the ultimate application of the calibration to field data, and in considering the significance of the control conditions of the calibration. The statistical method used for calculating the 95% confidence limits of the mass ratio is taken from Finney (147) and is shown in Appendix 1.

5.1.9. Pellet Treatment.

The mass of the pellet depends upon the extent to which it is dried after formation. The pioneer of the flour pellet technique, Bentley (118) allowed the pellets to dry in air, as he used only an approximate relationship between drops and pellets based upon a comparison of their respective diameters. This is not an accurate method because the shape of pellets varies, being almost spherical for small pellets, but dough-nut shaped with an almost hollow centre for large pellets. There is also considerable variation in the shape of pellets formed by drops of the same size. Laws first dried the pellets in air, then in an oven at 110° for one hour but comments (119) that "two hours would have been a better drying time as after one hour the pellets were still losing weight rapidly". Ker (22) who later followed Laws' technique fairly closely, used a short period of drying at 100°C before sieving, followed by further drying for one hour at 100°C .

Provided that exactly the same method is used for the calibration exercise and for the field experiments, the actual method will not influence the result. However, if a short drying period is used, errors are more likely to arise from variations in drying time, and so a standard procedure of drying to constant weight is to be preferred. Fig. 5.6. shows the effect upon the mass ratio of drying pellets for various lengths of time and using two different temperatures, and led to the adoption in the present investigations of a standard drying time of 12 hours at 105°C , both for the calibration and field experiments. After having been oven dried, pellets pick up moisture when exposed to the air. To reduce this absorption to negligible proportions the pellets should be allowed to cool in a dessicator and only removed immediately before weighing.

FIG. 5.5. VARIATION OF AVERAGE PELLET MASS IN GROUPS OF 20 PELLETS.



Meyer (121) states that "The importance of pellets being air dry to the core before placing in the oven cannot be over-emphasised. If still moist they tend to bake and brown like bread dough, causing variation in size and surface characteristics which affect sieving and weight". No evidence is given to support this, and in the present experiments special tests to investigate this point gave a quite different result. Several groups of pellets were made, and allowed to air dry for varying periods of time before drying to constant weight. The results, shown in Fig. 5.7., show that when the pellets are dried to constant weight, the period of air drying before oven drying is irrelevant. Measurements were also made of the size and shape of the different groups of pellets using a low power travelling microscope, but the size and shape were as unaffected as the weight. It was necessary to establish this point clearly, because whereas most previous studies have involved the direct collection of rain samples by hand, the present experiments used an automatic sampler to take samples at any hour of the day or night whenever a predetermined rainfall intensity was reached. The time elapsed between the rain and removing the sample thus varied, and although it would be possible to leave the sample for a fixed waiting time, it was much more convenient to start the 12 hour drying period at fixed times, so that the drying was completed either overnight or during the day.

After oven drying, the pellets are baked hard and may be sieved without any danger of breakage. A little loose flour which adheres to the surface of the pellets is dislodged during sieving, and the pellets are further cleaned before weighing. The exact procedure is described in Section 8.2.6.

5.1.10. Effects due to Flour Conditions.

The mass ratio is likely to be influenced by a number of conditions relating to the flour. In most cases all that is required is that the same conditions obtain for both the calibration and the collection of field samples, but the accuracy may also be influenced by some of the factors now considered.

a) Quality of Flour.

Even when all other variables have been considered there remain differences in the calibration results of different workers. It is possible that these are due to different flours having been used in various parts of the world.* Although this has been offered as an explanation for differences which are more probably caused by errors in technique, it is quite likely that there is some variation due to this cause. The practical solution is to minimise the risk

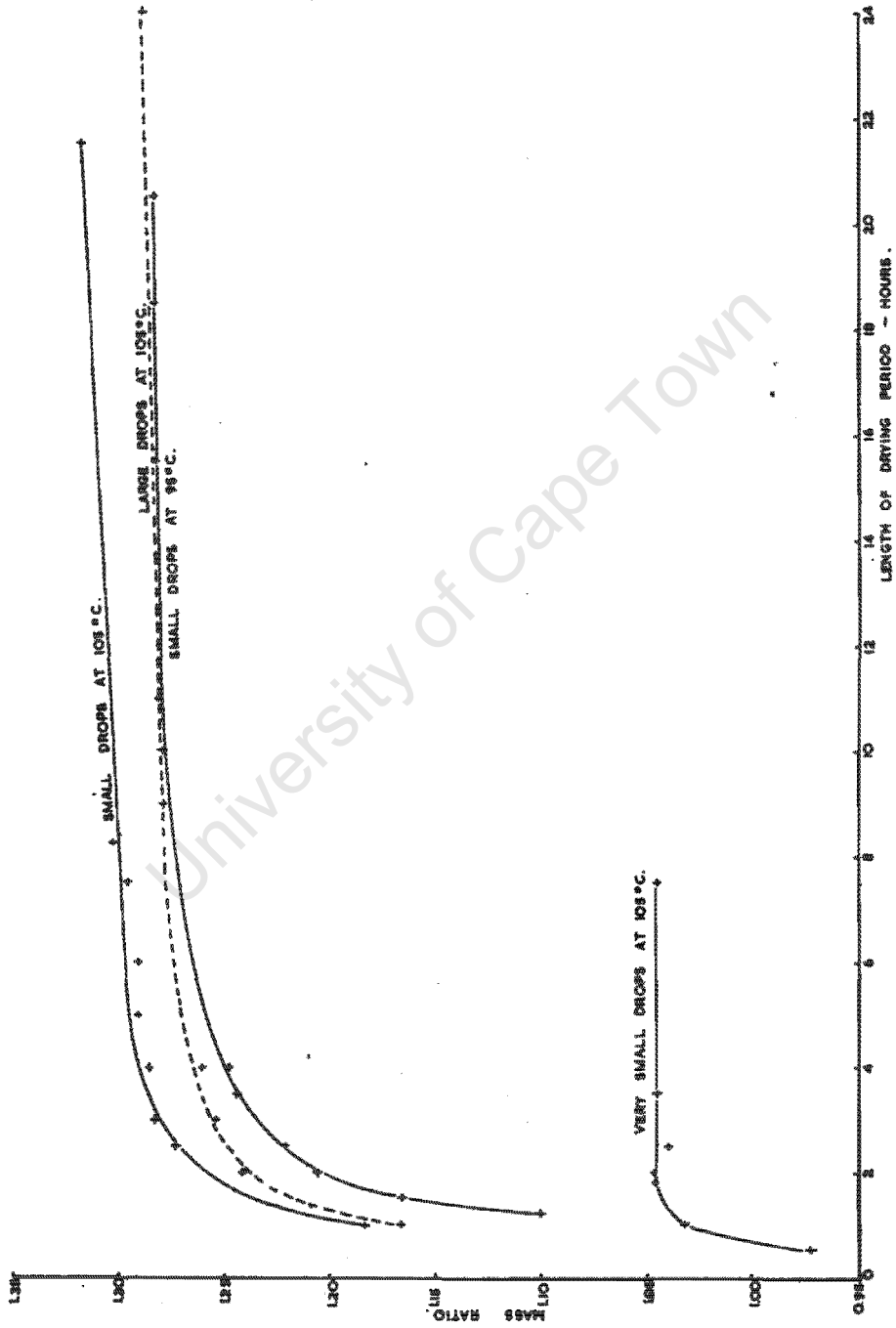


FIG. 3.6. EFFECT ON MASS RATIO OF LENGTH & TEMPERATURE OF DRYING PERIOD.

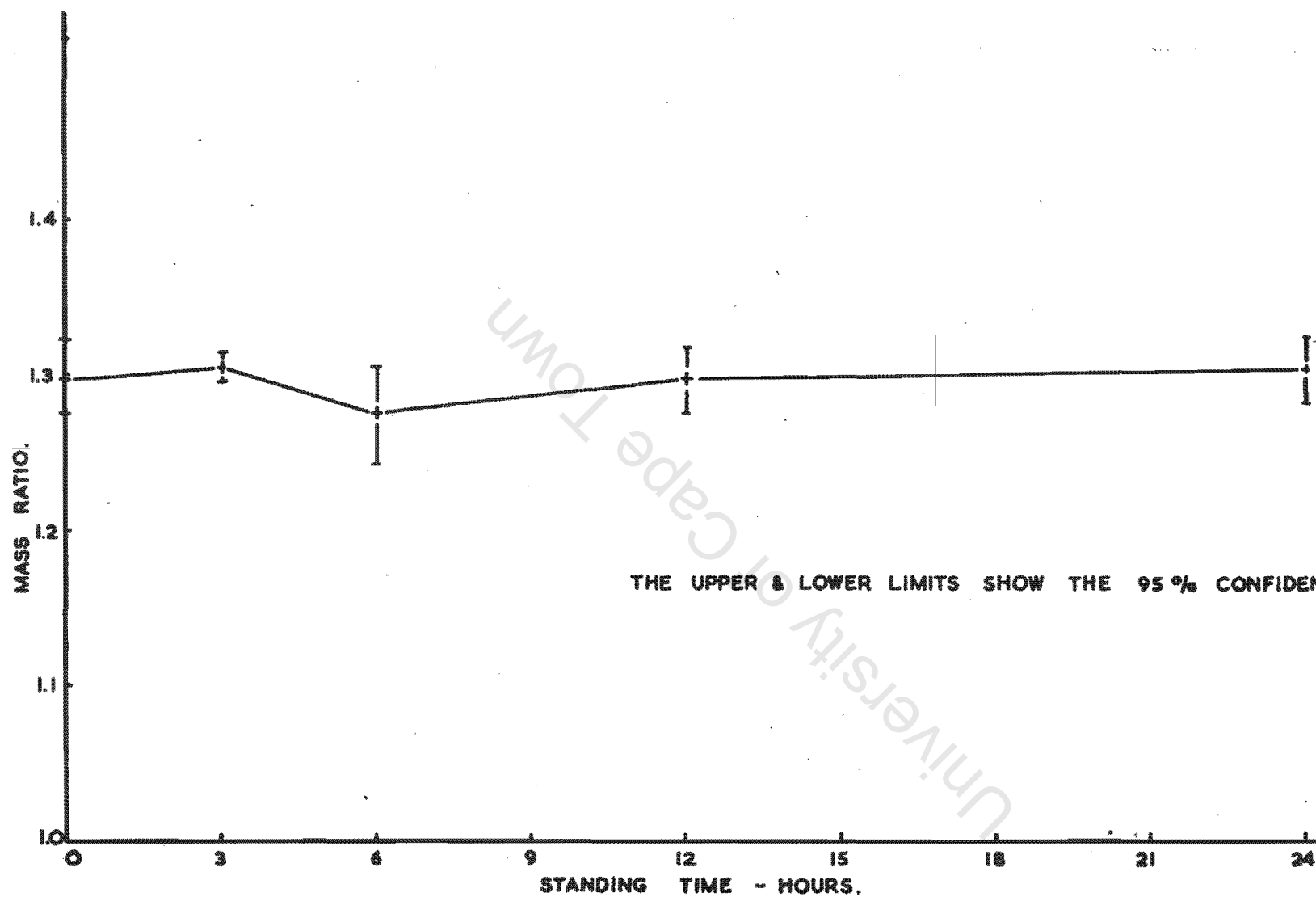


FIG. 5.7. EFFECT ON MASS RATIO OF VARYING THE STANDING TIME BEFORE DRYING FOR 12 HOURS.

by buying and storing as large a quantity of the same batch and brand as can be stored, preferably enough for the whole series of experiments.

b) Fresh or Old Flour.

Once the flour has been oven dried its properties are changed and it should be discarded. For large drops of about 4 mm. diameter the mass ratio changed from 1.26 using fresh flour to 1.29 using flour used in a previous experiment.

c) Preparation of Flour Pans.

A uniform method of filling the sample pans with flour must be adopted, and a convenient and simple way is to sprinkle it evenly into the pan by shaking a sieve full of flour a few inches above the pan. Laws and Parsons (119) felt that the size of pellet may vary if the flour were freshly sieved or had been standing for some time, and used only pans filled less than two hours before use. This point has also to be investigated because the automatic sampler would involve pans having to stand for various lengths of time. The results of this study plotted in Fig. 5.8. show that Laws' caution was unnecessary.

Two points which may reduce the accuracy of the experiment have been pointed out by Blanchard (123). Unless the depth of flour is sufficient to cushion the impact, some spattering of the large drops may occur, resulting in unnaturally small pellets. A depth greater than 2 cm. is required to avoid this. Secondly, Blanchard found that of the factors likely to cause this drop spatter, the most important is the flour surface. Laws and Ker both struck off the excess flour with a scraper after sieving, leaving a smooth surface. Blanchard showed that this causes drops more than 4 mm. diameter to spatter appreciably, throwing out one to three droplets, and that this could be avoided by leaving the flour surface unscrapped, so that the irregular surface with its peaks and valleys causes a less violent deceleration. Tests were carried out with rough and smooth flour and the results are shown in Table 5.2. When large drops fall on smooth flour, the variation is increased significantly, and to eliminate this possible source of errors unsmoothed flour was used both for the calibration and field samples.

Blanchard made another positive improvement in the flour pellet technique by introducing into the flour very small quantities of methylene blue dye. He found the optimum concentration to be 0.5 per cent of dye which had been previously passed through a 100 mesh sieve to remove any large particles. At this concentration the dye is hardly noticeable in the dry flour, but the pellets are a deep blue and easily seen in the flour. In the present experiments the

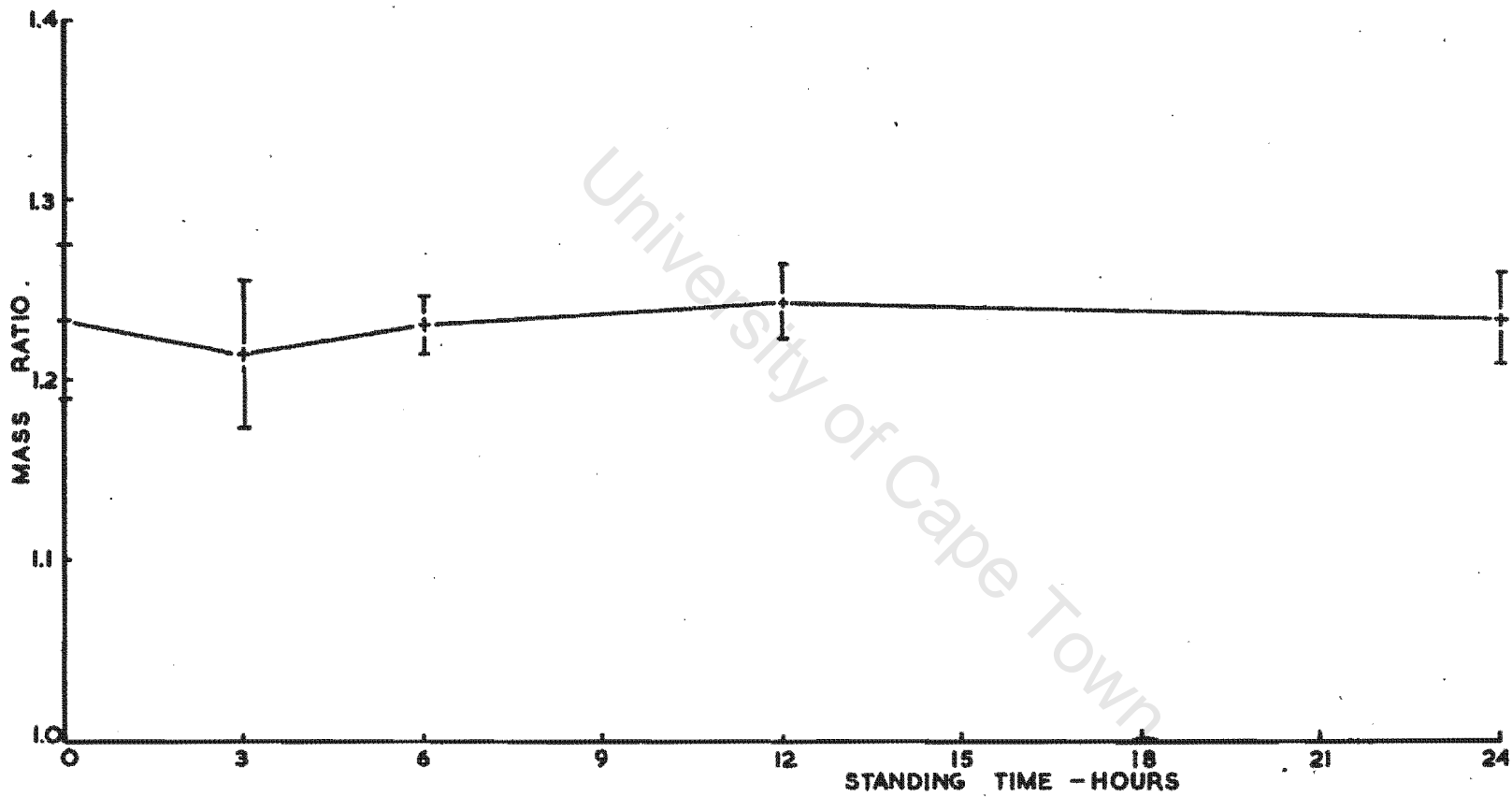


FIG. 5.8. EFFECT ON MASS RATIO OF ALLOWING PREPARED FLOUR PANS TO STAND BEFORE EXPOSURE TO RAIN.

dye was used in the calibration studies so that the position of each pellet could be seen and the correct number verified. Dye was not used in the field sampling of natural rain as it was found simpler to pass the whole flour mass through a fine sieve than to extract by hand the large number of variously sized pellets.

Meyer (121) covered the pellets with a sprinkling of flour immediately after taking each sample, on the theory that as the larger pellets penetrate farther into the flour than smaller ones they would have a different degree of contact with the flour. Sprinkling flour on top ensures that all are completely surrounded by flour. Since this cannot be done using an automatic sampler it was not used in the present calibration, but the effect was investigated to see if it might have affected Meyer's calibration. Table 5.3. shows that the variation of pellet size is not significantly reduced by the larger pellets produced. Meyer's results will have therefore been affected, but are no less accurate as the pellets were covered both in the calibration and in his tests.

5.1.11. Effect of Velocity of the Drops.

The effect of varying the impact velocity of the water drops on striking the flour was tested by allowing the drops to fall into the flour from different heights. The results show in Fig. 5.9. that the mass ratio is materially affected. The decrease in mass ratio when the drops fall farther and faster cannot be accounted for by reduction of drop mass by evaporation, as in section 5.1.6. the evaporation effects were shown to be negligible under the experimental conditions, so the change must be due to increased pellet mass. Presumably the fast-moving drops penetrate more deeply into the flour and make a larger pellet. If during the calibration experiments all the drops of various sizes fall the same distance, their velocity, expressed as % of terminal velocity, will be greater for the small drops than the larger, and the calibration curve will be in error.

Laws (39) showed that the velocity of a falling raindrop is seldom outside the range 90 - 100% of the still air terminal velocity for a drop of that size, with 95% as the most usual value. The calibration should therefore be carried out under these same conditions. Fig. 5.10. shows Laws' results for the height of fall required for a drop to reach 95% of its terminal velocity, and these were the heights of fall used in the present calibration. The difficulty of conducting the experiment with the fall of 26 ft. which is required for large drops has led previous workers to ignore this effect.

TABLE 5.2.

EFFECT OF ROUGH OR SMOOTH FLOUR ON MASS RATIO.

	Large Drops (4.75 mm dia)		Small Drops (2.2 mm dia)	
	Mass Ratio	Variance of mass Ratio	Mass Ratio	Variance of mass Ratio
Smooth flour	1.227	35.0×10^{-4}	1.240	1.54×10^{-4}
Rough flour	1.221	0.68×10^{-4}	1.250	1.74×10^{-4}

Testing homogeneity of variance

Large drops $F_{3.5} = 51.5$ (Significant @ 1%)

Small drops $F_{3.5} = 1.13$ N.S.

TABLE 5.3.

EFFECT OF COVERING FLOUR PELLETS ON MASS RATIO.

	Large Drops (4.75 mm dia)		Small Drops (2.2 mm dia)	
	Mass Ratio	Variance of mass Ratio	Mass Ratio	Variance of mass Ratio
Uncovered Pellets	1.221	0.68×10^{-4}	1.250	1.74×10^{-4}
Covered Pellets	1.199	0.47×10^{-4}	1.200	2.32×10^{-4}

Testing homogeneity of variance

Large drops $F_{3.3} = 1.42$ N.S.

Small drops $F_{3.3} = 1.33$ N.S.

Variation of mean mass ratio

Large drops $t_4 = 3.55$ Significant $P < 5\%$

Small drops $t_4 = 4.31$ Significant $P < 2\frac{1}{2}\%$

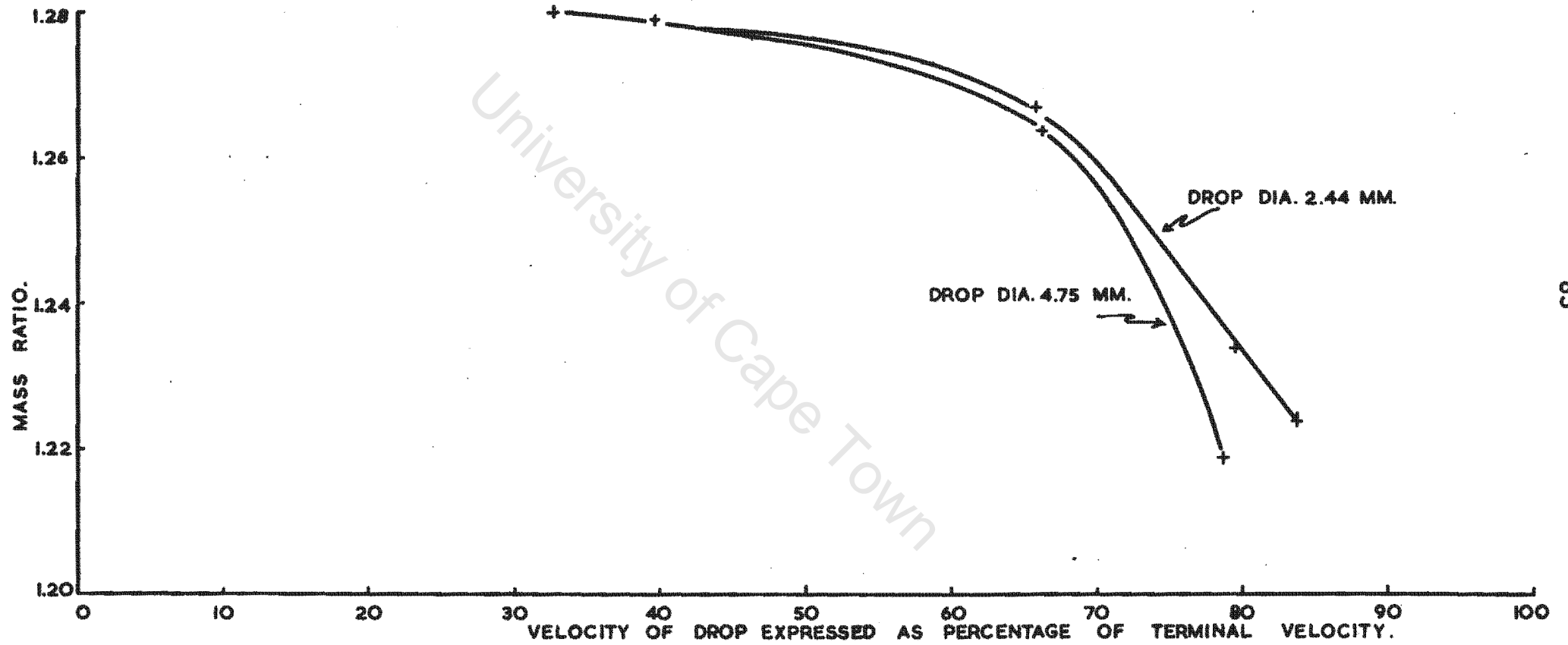


FIG. 5.9 EFFECT OF DROP VELOCITY ON MASS RATIO.

5.2. PRESENT CALIBRATION.

5.2.1. Control Conditions.

The present writer's calibration was carried out under the optimum control conditions established in Section 5.1. That is a suitably large number of drops and pellets were measured, (four groups of ten for large drops, four groups of twenty for small drops), and from the standard errors an estimate was calculated of the 95% confidence limits for the drop mass, pellet mass, and mass ratio. The drops were formed slowly and at a constant rate of formation. An air stream was used to blow away the satellite drops, and the drops were caught in oil to prevent evaporation. The pellets were formed by drops falling at 95% of terminal velocity into uncompacted unsmoothed flour, and were oven dried to constant weight before weighing. The results are presented in Table 5.4.

5.2.2. Interpretation of Results.

When the drop mass is plotted against pellet mass (Fig. 5.11) it is obvious that there is a very close and apparently direct relationship, and the least squares linear regression equation is

$$\text{Drop mass (mgm)} = 1.2624 \text{ Pellet Mass (mgm)} - 0.19285 \quad (1)$$

The correlation coefficient is highly significant at $r = 0.999$.

This simple relation is, however, misleading. The true form of the curve must pass through the origin as a drop of zero mass cannot yield a positive pellet, and so there must be a departure from this linear regression at very small values. To clarify this the data is plotted on logarithmic scales in Fig. 5.12. The relationship is again almost linear, but the non-linearity is in fact significant. The confidence limits are not shown in Figs. 5.11. and 5.12. because as will be seen from Table 5.4. they would be barely visible on these scales. The best interpretation of the data is made by using Laws' "mass ratio", the ratio of drop mass to pellet mass. In practice the mass of a raindrop will be calculated by multiplying the measured pellet mass by this mass ratio, and so a variation of 10% in the mass ratio will result in a 10% variation in the computed drop mass. Considering again Fig. 5.11., the graphical interpretation of the mass ratio is the slope of a line from the origin to any particular point, and in fact this varies considerably, especially at small values, although the variation is masked by the fact that the slope of the regression line is nearly 45% (i.e. the mass ratio is nearly unity), and very nearly passes through the origin.

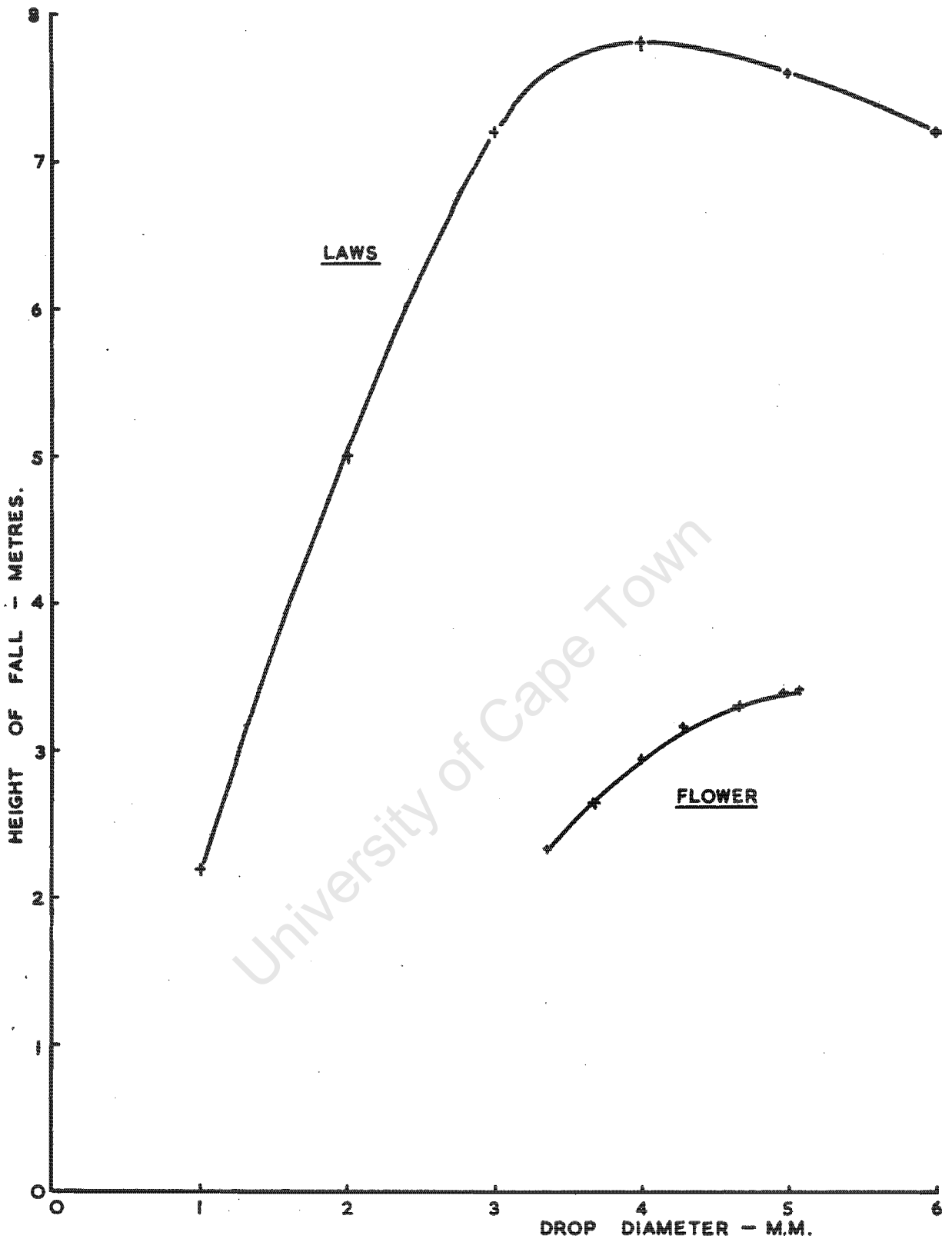


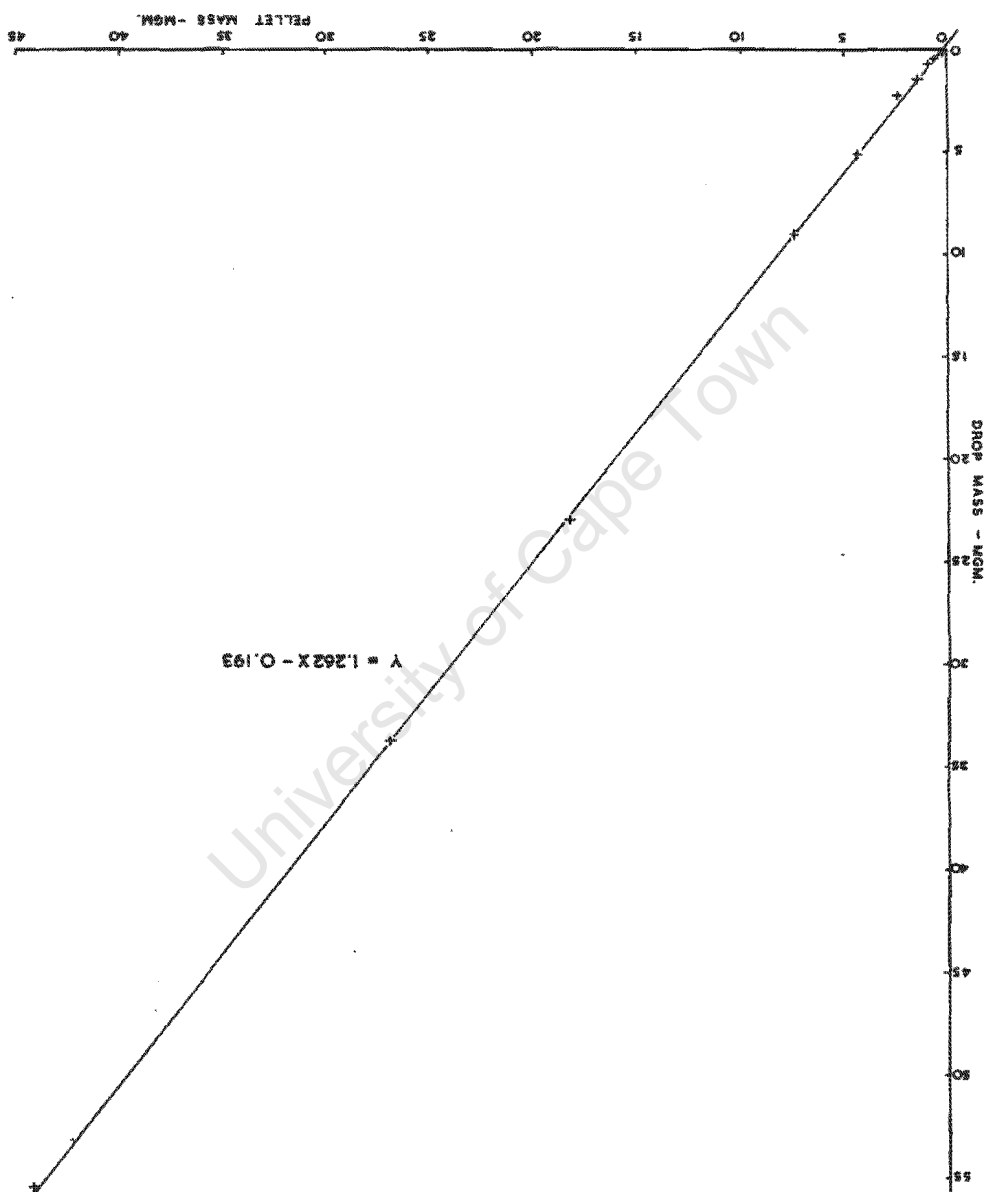
FIG. 5.10. RELATION BETWEEN DROP SIZE AND HEIGHT OF FALL REQUIRED TO REACH 95 % OF TERMINAL VELOCITY.

TABLE 5.4.

FLOUR PELLETS CALIBRATION RESULTS.

Drop	No. of Drops	Drop mass mgm	Standard Error (S.E.)	Coefficient of Variation (C.V.) in groups of (10 or 20)	C.V. (20 drops)	95% Limits (t=3.182)	Pellet Mass mgm	S.E.	C.V. in groups 10 or 20	C.V. (20)	95% Limits (t=3.182)	Mass Ratio	95% Limits $\pm$	S.E.	C.V.	Upper and Lower Limits of mass Ratio	
1	20	0.0800	.0041	5.08	5.08	.013	0.1219	.0024	1.96	1.96	.0076	0.656	0.104	.041	6.20	0.760	.552
2	20	0.2038	.0048	2.35	2.35	.015	0.2625	.0074	2.82	2.82	.024	0.766	0.060	.023	3.02	.835	.716
3	20	0.3117	.025	8.02	8.02	.080	0.370	.014	3.78	3.78	.044	0.843	0.170	.066	7.33	1.013	.673
4	20	0.5787	.013	2.27	2.27	.041	0.6650	.0147	2.21	2.21	.047	0.870	0.090	.035	4.04	.960	.780
5	20	0.8587	.027	3.12	3.12	.086	0.8775	.0029	0.33	0.33	.009	0.979	0.076	.030	3.02	1.055	.903
6	20	1.567	.043	2.74	2.74	.137	1.456	.018	1.23	1.23	.06	1.076	0.070	.027	2.55	1.146	1.006
7	20	2.382	.110	4.62	4.62	.35	2.354	.083	3.51	3.51	.26	1.012	0.097	.038	3.73	1.109	.915
8	10	5.208	.062	1.19	0.84	.20	4.283	.075	1.75	1.24	.24	1.216	0.044	.017	1.41	1.260	1.172
9	10	9.235	.055	0.60	0.42	.18	7.410	.088	1.19	0.84	.28	1.246	0.035	.014	1.09	1.281	1.211
10	10	23.055	.063	0.27	0.19	.20	18.133	.535	2.95	2.09	1.70	1.271	0.102	.040	3.12	1.373	1.169
11	10	33.93	.04	0.12	0.08	.12	26.86	.31	1.15	0.81	.98	1.263	0.037	.014	1.14	1.300	1.226
12	10	55.51	.24	0.43	0.30	.76	44.33	.44	1.00	0.71	1.40	1.252	0.029	.011	0.90	1.281	1.223

FIG. 5.11. RELATION BETWEEN DROP MASS AND PELLET MASS.



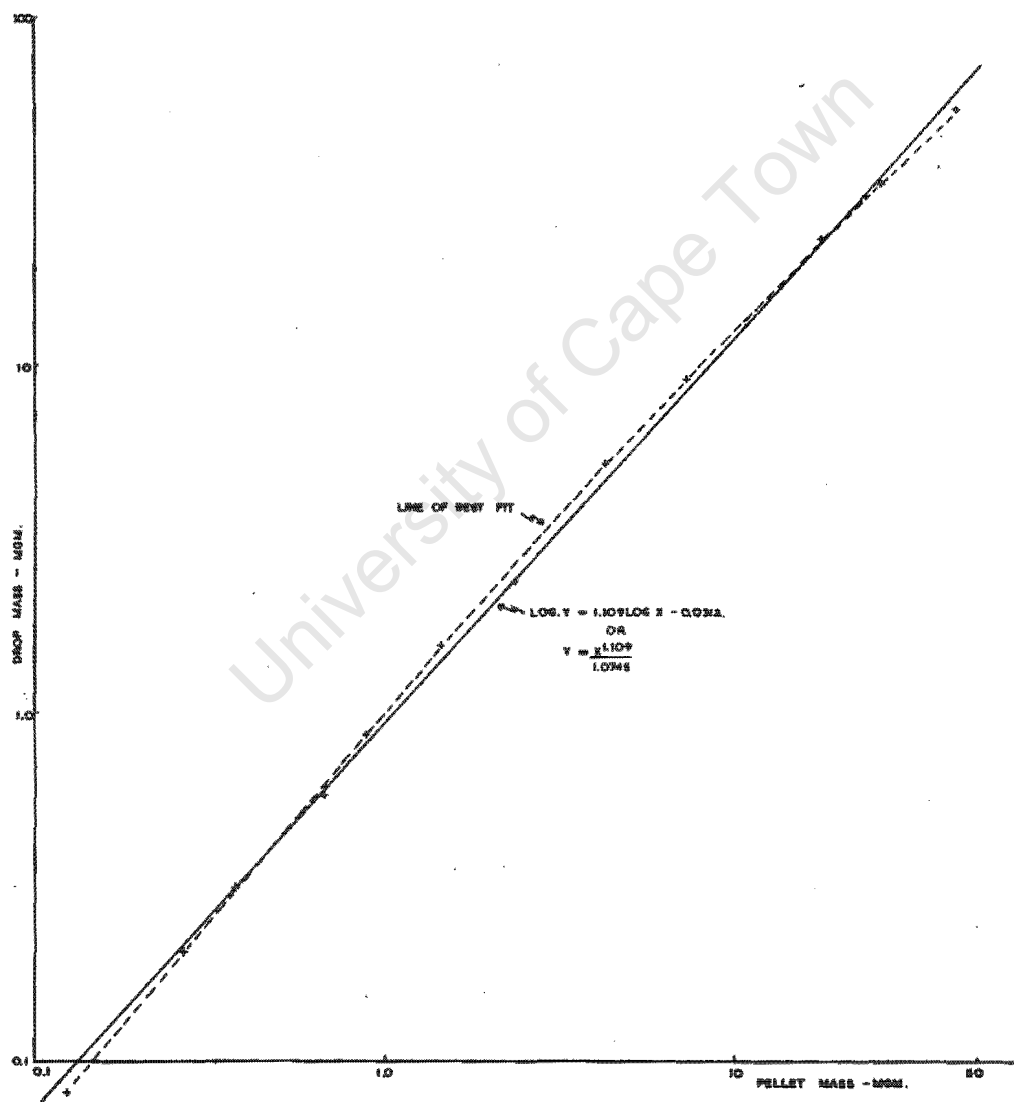


FIG. 2.12. RELATION BETWEEN DROP MASS AND PELLET MASS.

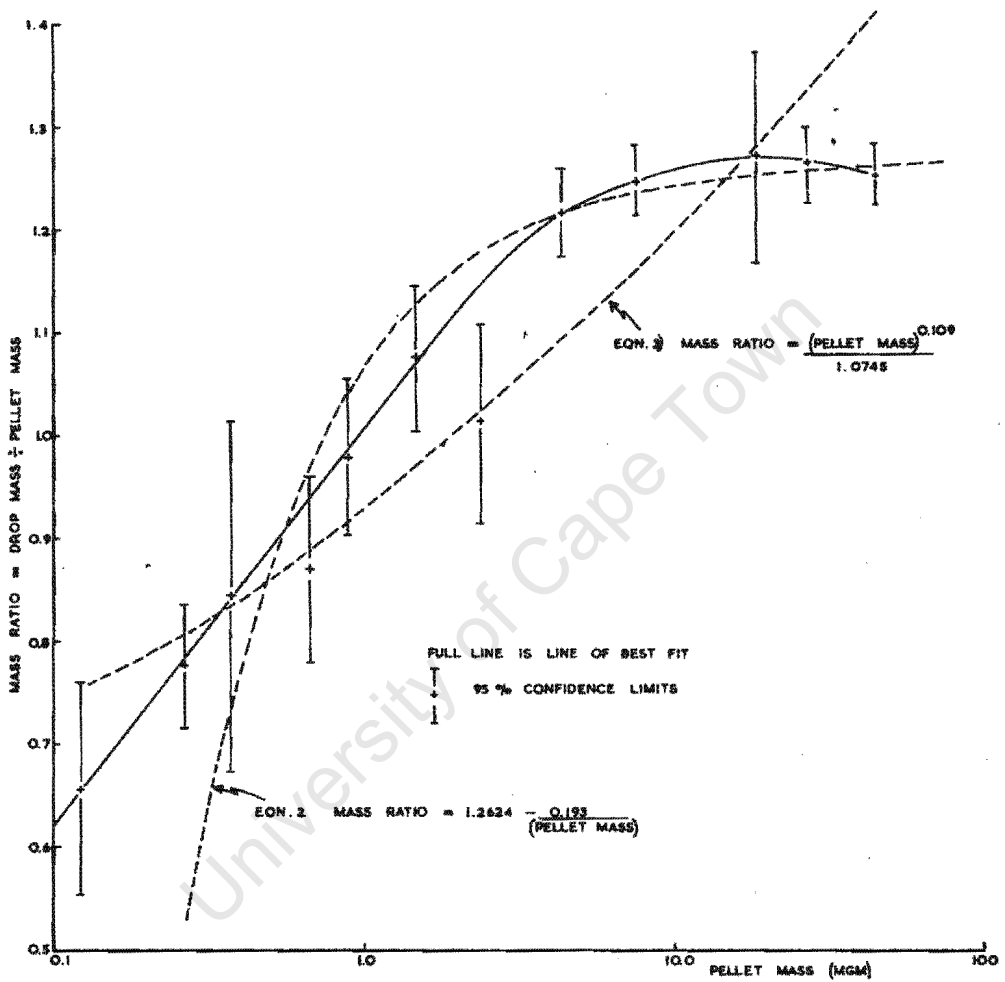


FIG. 5.13. RELATION BETWEEN MASS RATIO & PELLET MASS.

In Fig. 5.13. the mass ratio is plotted on semi-logarithmic scale against pellet mass, with the 95% confidence limits for mass ratio calculated by Finney's method (Appendix I). The significance of the non-linearity of Fig. 5.12., and of the small intercept of Fig. 5.11. and equation (1), is now shown by the large changes in mass ratio for small pellets. The linear regressions from Figs. 5.11. and 5.12. transform to

$$\text{Mass Ratio} = 1.2624 - \frac{0.193}{(\text{Pellet Mass})} \quad - (2)$$

$$\text{and Mass Ratio} = \frac{(\text{Pellet Mass})^{0.109}}{1.0745} \quad - (3)$$

These equations are also shown in Fig. 5.13. and it is clear that neither adequately describes the relationship over the whole range. Equation (3) fits the data well for small pellets but not for large pellets and the opposite is the case for Equation (2). Attempts to rectify the data to a straight line relationship in order to calculate a regression equation have not been successful, and the trend line shown is that of best fit by eye.

A hypothesis which partially explains the nature of the true relationship and the departures from regression equation (2) can be advanced. The fact that the regression line of Fig. 5.11. cuts the abscissa with a positive intercept implies that a pellet of zero mass requires a negative drop mass. This intrinsically is nonsense, but what it may suggest is that a certain proportion of the drop does not go towards forming the pellet, but is dissipated in the surrounding flour. If one assumes that this dissipated moisture is proportional to the surface area of the drop, then it will be a function of the square of the diameter, and since the mass is a function of the cube of the diameter, the result would be that as the drops increase the mass increases more rapidly than the dissipated moisture. In other words the effect of this dissipation will be most marked with the smallest drops, and the mass ratio will be lowered more and more as drop size decreases. This is in fact exactly what happens.

Further, the regression equation of Fig. 5.11., with its constant intercept, implies that this dissipated moisture is constant, or rather it gives an averaged value. So when the equation is transformed to Equation (2) and plotted in Fig. 5.13. it gives values too low for small drops (because the averaged dissipated moisture is too large) and it becomes asymptotic to the value of 1.2624 as the effect of the dissipated moisture becomes negligible with large drops.

This hypothesis thus offers a rational explanation for the increase of mass ratio. What is less easy to account for is the

fact that the mass ratio apparently reaches a maximum at a pellet mass of 18 mgm. and then decreases slightly. The shape and form of the pellets does vary, and while small pellets are circular the large ones have a characteristic shape best likened to that of a ring type doughnut with a thick membrane across the hole. This may account for the largest pellets having a relatively higher mass and lower mass ratio. However, while the variation from a uniform mass ratio involves a 100% difference at the lower range, this reduction at the high range is less than 2% and not worth pursuing. In the practical application of these results it has been assumed that this slight decrease in mass ratio is real, and the trend line of Fig. 5.13. has been used to determine the values of mass ratio actually used in the calculation of the results.

5.3. DISCUSSION OF EARLIER CALIBRATIONS.

The relationship between the mass of the drop and the mass of the flour pellet has been determined experimentally by a number of other workers, and their results will now be discussed briefly in relation to the control conditions established in Section 5.1., and the results presented in Section 5.2. It was shown in 5.2. that plotting drop mass against pellet mass is not sufficiently sensitive to show the relationship adequately, and so in Fig. 5.14. the more sensitive mass ratio plot is used to compare the several results.

The earliest calibration was undertaken by Bentley (118) who in 1904 first used the flour pellet method. He did not establish a very precise relation, merely saying that the pellets were found "to correspond very closely in size with the raindrops that made them". This may mean that he assumed the average diameters of drop and pellet to be equal, or that a simple ratio was established between the two diameters. Since no more detail is given by Bentley we are not able to discuss how his result may have been influenced by this over-simplification.

Laws (39) next reports on the method in 1941 when he used it to measure the size of water drops whose fall velocity was being studied, and again (Laws and Parsons, 119) to study natural rainfall. The same calibration was used in both studies. Laws appreciated the need for precision and plotted mass ratio against log. pellet mass as the most accurate and convenient way of presenting the data. His original data is not available and has been carefully extracted from his graphs. The fact that the whole trend is for much lower mass ratios is due to his having only partially dried the pellets, and need not necessarily have caused an error when applied to his results. The effect of drying to constant weight would be to

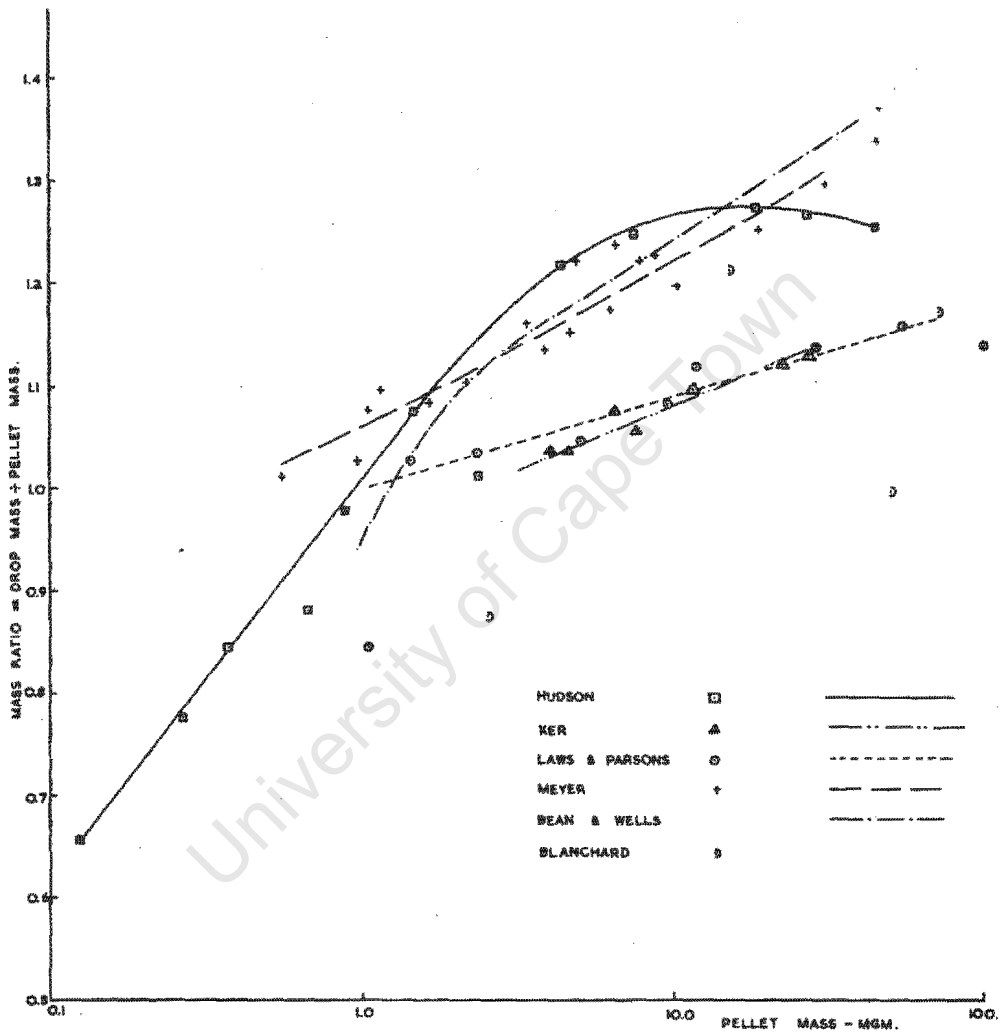


FIG. 5.14. COMPARISON OF SEVERAL MASS RATIO CALIBRATIONS.

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increase all the mass ratios, with a greater increase for the larger drops, i.e. bringing it more into line with the present writer's results. Probably the most important feature of Laws' results is that he records decreased values of mass ratio at both ends of his range, but failed to interpret this. The mass ratio value of 0.845 at pellet mass of 1.035 mgm. was assumed to be experimental error on the theory that the pellet mass could not be greater than the drop mass i.e. mass ratio could not be less than unity. In fact there are no grounds at all for this assumption, and values below unity certainly can and do occur. Laws was unfortunately working before the development of the use of co-axial air streams to produce very small drops and was unable to reproduce such small drops to verify his result. He makes no comment on the fact that his mass ratio value also falls slightly for the largest drop made. Other points which probably influenced Laws' results are evaporation during collection of drops, catching the satellite drop (this was observed but considered negligible), and using flour pans with smoothed surface. The height of fall is not mentioned, nor the variation among the measured groups of drops or pellets. The trend line shown on Fig. 5.14. is that shown by Laws, but it will be seen that an equally good or better fit could be obtained with a curve concave downwards. This applies equally to Ker's data.

Blanchard (123) used the method to study drop size distribution in natural rain, although he later turned to the filter paper stain method as being better suited to his requirements. Again the original data are not available, but are presented graphically as the relation between drop diameter and cube root of pellet weight (i.e. a function of average pellet diameter).

The expression given by Blanchard is

$$\text{Drop diameter (mm)} = 1.29 \times (\text{Pellet Mass (mgm)})^{0.333}$$

which, assuming a specific gravity of 1 for water, transforms to

$$\text{Drop mass (mgm)} = 1.124 \times \text{Pellet mass (mgm)}$$

$$\text{or Mass Ratio} = 1.124$$

When the data are extracted from Blanchard's graph and plotted in Fig. 5.15. it is seen that the mass ratio varies between 0.87 and 1.21 so his equation is an unjustified over-simplification. It arises from assuming a straight line relationship passing through the origin, and the ever present danger of extrapolation beyond experimental values is demonstrated. Blanchard says "Although no drops were produced below 1.62 mm. in diameter, it is reasonable to assume that the linearity of the plot should exist down to zero". It would have been more appropriate to say that "since no drops were produced below this size, there are no grounds for assuming that

the relationship holds beyond this point". Blanchard's experimental conditions are not given in sufficient detail to warrant attempts to explain the large and random scatter of his results, and the work is noteworthy mainly for the introduction of methylene blue dye to the flour, and for establishing the fact that an unsmoothed flour surface is desirable.

Ker (22) followed Laws and Parson's work very closely, the only modification being that the pellets were dried a little longer, although still not to constant weight. A height of fall of only 8 feet was used, and although pellets larger than 30 mgm. were discarded because their shape was observed to differ from those of natural rain, the error would in fact have applied to the whole calibration since even the smallest drop would only have reached about 75% of terminal velocity after such a small height of fall. Other possible sources of errors are variation of drop size, evaporation during collection, collection of satellite drops, and a smooth flour surface. The variation of pellet weight had a maximum range of 11.4%, corresponding to a coefficient of variation of approximately 3%, a reasonable value, but no measurement was made of drop variation so no confidence limits can be established for the variation in mass ratio.

Schleusener (120) used the pellet method to study the size and kinetic energy of drops from irrigation sprinklers. His calibration was done with plaster of paris, and the drops of various sizes projected from the periphery of a spinning disc. After establishing a correction factor for the difference between plaster of paris and flour, this correction was applied to Laws' calibration. Apart from possible sources of error in Laws' original work, this method of drop production is suspect because the smaller drops are projected at the greatest velocity, and the largest drops more slowly, which is the reverse of the natural conditions of both rainfall and drops from an irrigation spray.

Beans and Wells (92) gave a calibration curve shown as log. pellet mass (mgm) against drop diameter (mm). Transposed to the mass ratio form the curve is shown in Fig. 5.14., but the authors are unable to recall the original source of the information, and in the absence of the experimental data and conditions it would be unfair to comment further than that it appears to follow the present writer's results fairly closely.

Meyer (121) undertook the most carefully controlled calibration previously reported. Some unnecessary controls were in

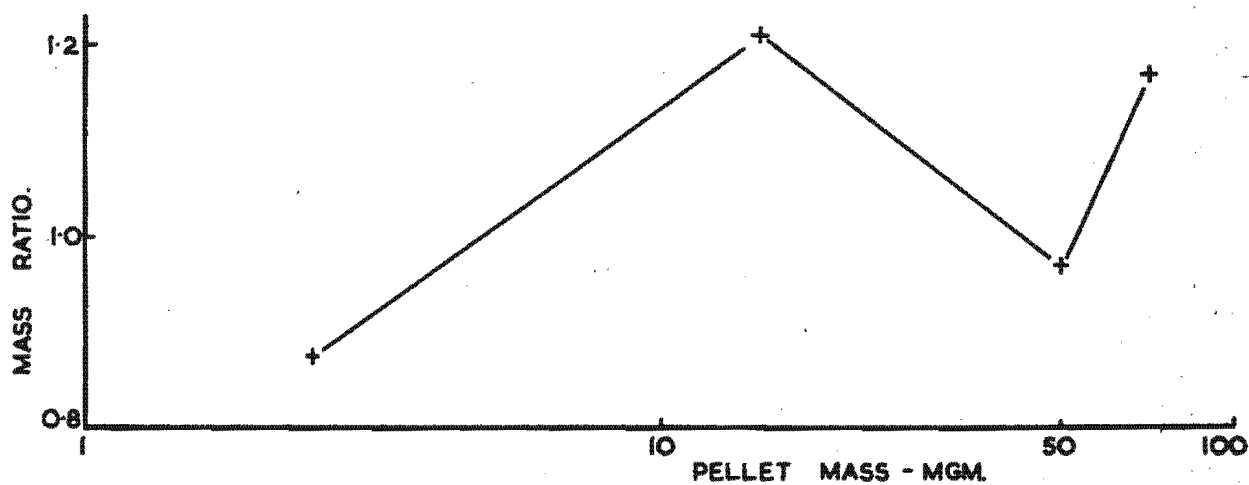
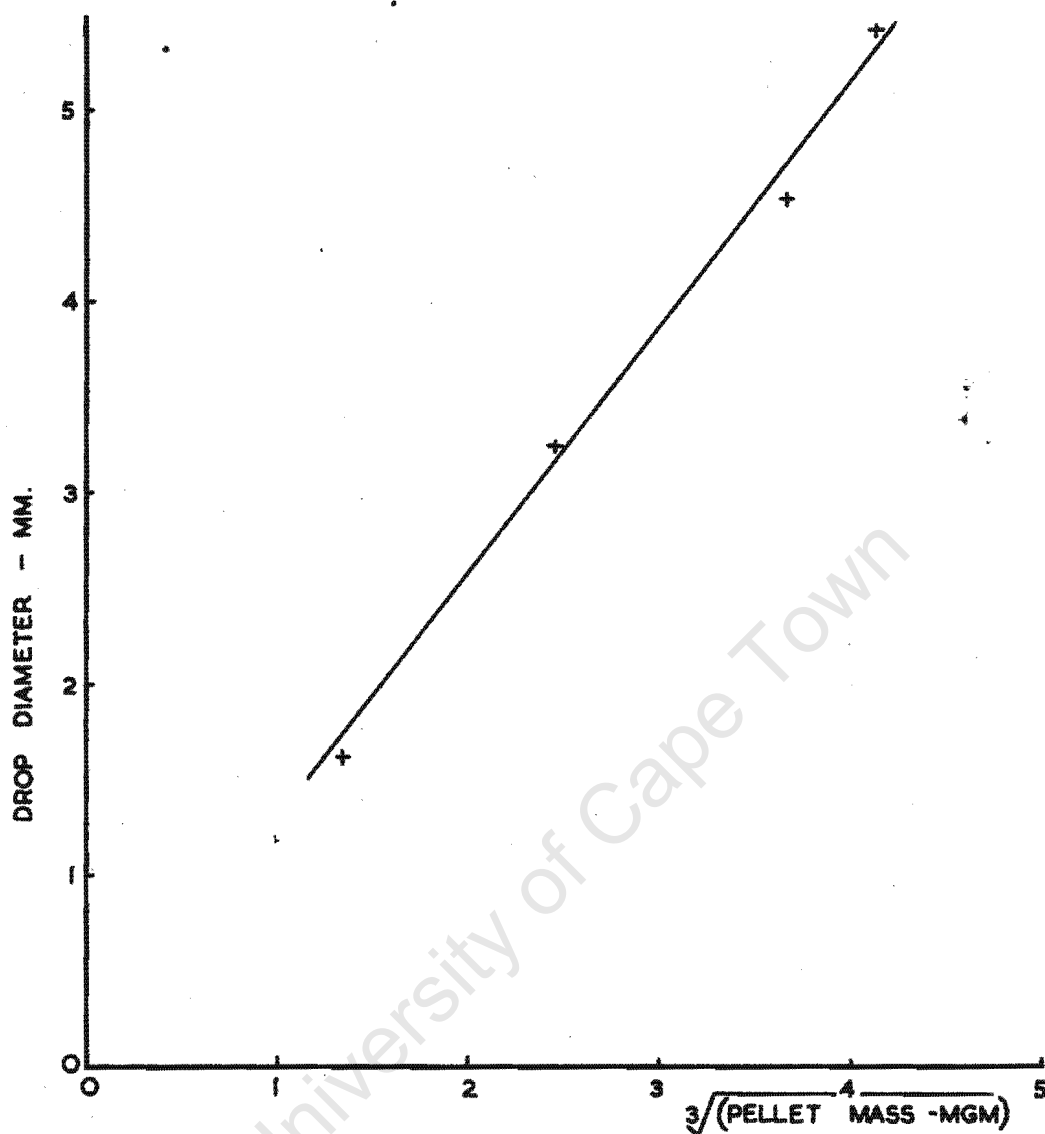


FIG. 5.15. BLANCHARD'S CALIBRATION DATA.

fact applied, such as saturating the air used to blow the small drops off the dropping point, and air drying the pellets before oven drying. Other necessary controls were not applied and possible sources of error are due to variation in drop size, evaporation during collection, catching satellite drops, the use of levelled flour and the use of a height of fall of 12 feet only. The regression is expressed by Meyer as

$$\bullet \quad \text{Drop mass (gm)} = 1.617 (\text{Pellet weight (gm)})^{1.061}$$

on the assumption that the data can be rectified to a straight line on a plot of log Drop mass against log. Pellet mass. In the mass ratio form, this regression line (Fig. 5.14.) shows a curvature concave upwards, which suggests that this equation is not in the best form, as all the other calibrations are straight lines or curves concave downwards, but the scatter is too wide to permit of a trend line being fitted by eye with any greater accuracy.

In considering all these calibrations there is one variable which cannot be quantitatively evaluated and which may account for some of the differences, and that is the flour used. Variations may be caused by milling methods or additives, and although a number of possible errors in techniques have been eliminated, and standard control conditions have been established, use of the flour pellet method should always be accompanied by a careful calibration.

CHAPTER 6.

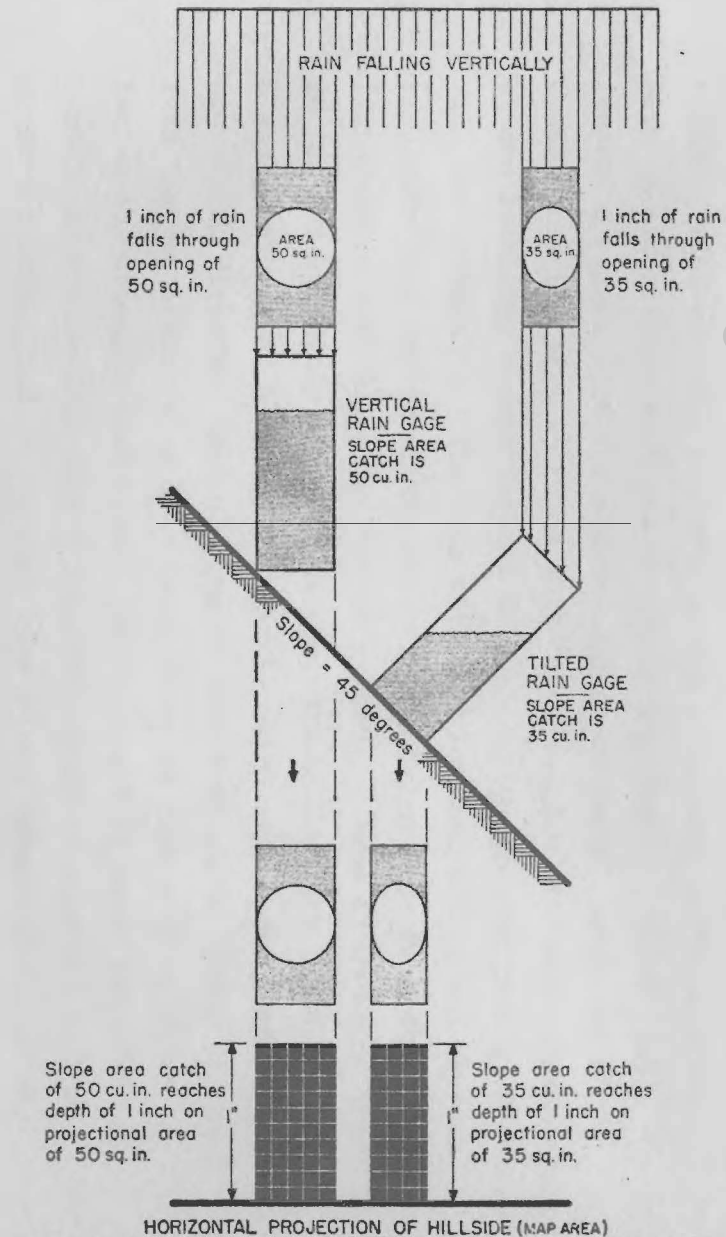
THE EFFECT OF WIND ON RAINFALL CHARACTERISTICS.

6.1. EFFECT OF WIND ON MEASUREMENTS OF QUANTITY AND INTENSITY OF RAINFALL.

If wind blows horizontally over the ground surface, a horizontal component of velocity is added to the vertical fall under gravity, and the rain strikes the ground at an inclined angle, and with a resultant velocity greater than would obtain in still air. Turbulence may add small vertical components to the wind velocity, but such variations are usually local or temporary, and consideration of wind as a horizontal vector only is not an over-simplification. A rain gauge set vertically presents to inclined rain an effective collecting area smaller than the area presented to vertical rain. When the ground surface is flat no problem arises as the rain collected is a true sample of that reaching the ground, but since quantities (or intensities) of rainfall conventionally relate to depths (or rates) per unit area of the horizontal projection (map area) of ground surface, errors arise when inclined rain is recorded by a vertical gauge on an inclined ground surface. The particular case of rain normal to ground surface is shown in Fig. 6.1. taken from Hamilton (148). The error of a vertical gauge is proportional to $\sec \alpha$, where α is the angle of the ground surface with the horizontal, and in mountainous country where α is of the order of 45° or more the error can be serious and has led to the increasing practice of setting rain gauges normal to the average ground slope. The present studies are related to arable slopes where α seldom exceeds 7° (approximately 12% slope) and the error due to this slope (1.0075) can be ignored. All measurements of quantity and intensity have therefore been made with horizontal collecting areas.

6.2. EFFECT ON FALL VELOCITY OF RAINFALL.

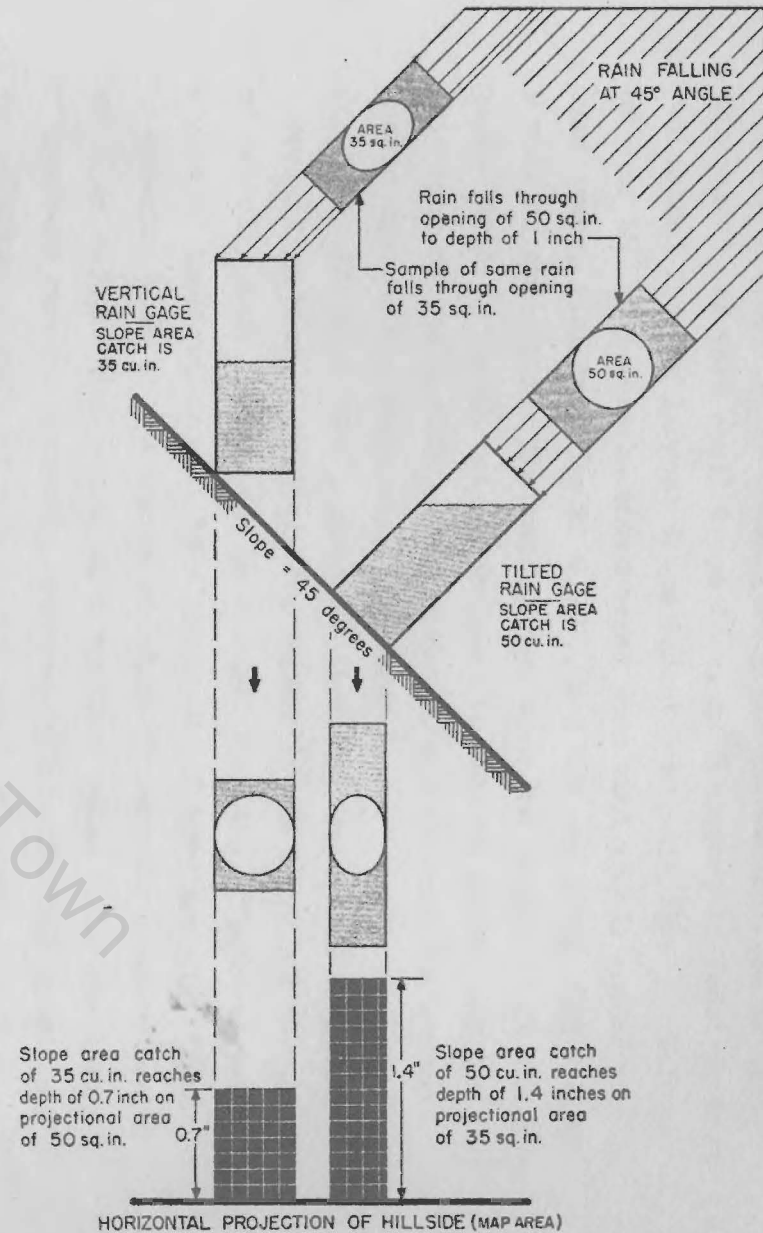
The angle of inclination of rain with the vertical (θ°), and the resultant velocity of falling rain, depend on the relative values of wind speed and free fall velocity of rain. The terminal



How rain, falling vertically on a slope, is sampled equally well by a rain gage placed either vertically or normal to the slope.

FIG. 6.1.
THE EFFECT OF
INCLINED & VERTICAL
RAIN GAUGES.

(FROM HAMILTON, 148)



How inclined rain falling on a slope is incorrectly sampled by a vertical rain gage and correctly sampled by a tilted gage.

velocity of water drops falling in still air varies from 12 feet per second for very small drops 1 mm. in diameter, to about 30 feet per second for the largest drops (about 5 mm. diameter). Values of θ of 45° will thus be encountered when wind speeds are of the same order, i.e. from 8 - 22 m.p.h., and for any given wind speed θ will be greater for the small drops than the larger. It would be impracticable, though not impossible, to measure separately the inclination of the various sizes of drops, and instead the average inclination of the whole rain is measured.

If, as in the present studies, the object is to seek correlations between quantity (or intensity) of rain and functions of velocity such as momentum or energy, then the effects of varying angles of inclination must be eliminated (if they are significant) by relating both to the common standard of what the measured value would be without wind - i.e. with vertical rain. The quantity of inclined rain is correctly measured by a horizontal gauge but the velocity of inclined rain is increased by secant θ . The correlation must therefore be tested between

$$Q \text{ (measured) and } (V \text{ (measured)} \div \sec \theta)$$

$$\text{i.e. } Q_m = f(V_m \cos \theta)$$

Later (6.4.) the significance of this correction for wind will be considered in relation to measured values of θ . It will of course be more important in the case of kinetic energy ($\propto v^2$) than of momentum ($\propto v$).

6.3. MEASUREMENT OF DIRECTION AND INCLINATION OF RAIN.

Earlier measurements of direction and inclination show some striking wind effects, but this is not surprising as these studies were in areas where wind was obviously important. Wicht (149) measuring rainfall in the mountainous experimental catchment of Jonkershoek (S. Africa) found that "of a total of fifteen rains measured at one locality, eleven fell at an inclination greater than 45° degrees with the vertical". The same data further analysed by van Heerden (20) show that twelve of the same fifteen rains came from directions lying within a 60° degree sector in azimuth. Free (150) found that in ten out of thirty nine storms recorded in New York State, U.S.A. θ was greater than 45° , and this inclination was so combined with prevailing direction that sloping erosion test plots facing directly into the prevailing wind lost three times as much soil as plots facing the opposite direction. In the light of these and similar results it was obvious that the effect should be measured in the present studies, but at the same time it was anticipated that the

effects would be less severe in sub-tropical convective thunder-showers. This prediction has in fact been confirmed both by other studies (Rose, 19) and by the present investigations.

A number of instruments have been designed to measure the angle of inclination and direction of wind. Pers (151) in 1932 designed a gauge for which he coined the name 'vectopluiometer' consisting of four vertical orifices facing the four cardinal points of the compass. The amounts of rain caught by each orifice are considered both in relation to each other and in relation to the amount caught by a fifth horizontal orifice, and a rather cumbersome mathematical treatment allows the computation of both direction and inclination. A variation on this design by Fourcade (152 and 153) was used by Wicht in the Jonkershoek experiments previously mentioned.

A different type of instrument was used by Hamilton (148 and 154) for the San Dimas, California, experiments. This "consisted of a horizontal and a vertical funnel mounted on a rotating head which was kept pointed into the wind by a vane. Rain caught by the funnels was directed into separate compartments of a receiving tank, one compartment for each quadrant of the compass for each funnel". Van Heerden (20) used a similar 'into-wind' rotating gauge, but with seven collecting funnels at different angles of inclination to the vertical, ranging from horizontal to vertical with 15° intervals. Each funnel had a separate collecting vessel and the whole apparatus was mounted on a freely rotating platform kept into the wind by a vane. Such devices are complicated to build and maintain, with a delicate balance required between free rotation and damping of overswing in gusty winds. Hamilton found the San Dimas model "complicated to build and use" and later turned to a fixed model of the Pers type. Van Heerden (155) subsequently showed that, apart from mechanical deficiencies, an into-wind instrument is inherently unsound on theoretical grounds, when, as is usually the case, changes of direction and inclination occur during the storm. Such a storm may correctly be described by a single vector representing the mean amount, angle, and direction, but such a vector must be the summation of similar vectors for each part of the storm. Neither the horizontal nor vertical components of the vectors may be averaged, as occurs with swinging gauges. The San Dimas type correctly registers direction in azimuth (at least by quadrant) but incorrectly averages the effect of inclination, whereas van Heerden's machine correctly registers inclination (within the seven classes) but incorrectly averages the directional effect.

The disadvantages of both these types have been overcome

in the instrument used in the present studies. Farbrother (156) designed this instrument for studies of the spread of cotton disease in Uganda, and used it to measure prevailing wind directions. Rose (19) later showed that it could also be used to determine the inclination of rain. It consists of three identical gauges set on a vertical stand with each collecting funnel at 45° to the vertical, and facing outwards in directions equally spaced 120° apart in azimuth. (See Plate 6.1.). Each funnel leads to a separate measuring container. Comparison of the catch in the three funnels, each with each other, allows a calculation of both angle and direction of the storm. Rose has made a detailed analysis involving the computation of the effective entry area of each funnel for all possible combinations of angle and direction - an extremely laborious exercise in three dimensional geometry. His results are reduced to a single graph from which both angle of incidence and direction may be read off directly for computed values of the ratios 'greatest catch to least catch', and 'greatest catch to second least catch'. Rose's work thus makes available a very simple and efficient method, which was used in the present investigations. There are two limitations or possible sources of error. a) If conventional gauges are used there is the possibility of some rain splashing out of the funnel. This was reduced, but probably not eliminated, by using the 'Snowdon' type gauge with deep funnel; b) the instrument is only effective where θ is less than 45° . Further, a storm with an indicated average θ of say 40° may include some portions of rain at say 50° which have not been correctly recorded, so introducing an error. This error decreases rapidly as the average inclination falls below 45° . In fact during the present studies only one storm was not recordable (θ greater than 45°) and one may possibly be in error (θ between 40° and 45°), so this possible disadvantage does not apply to studies of convective rain. Two possible errors were eliminated. 1) The tilted gauges have a low spot at the lower side of the funnel which is not drained by the centrally placed drain tube. This was overcome by filling this space with putty. 2) Evaporation of the collected rainwater was minimised by running the water through polythene tubing into closed jars with an inverted U-tube air vent.

There remains one defect basic to any instrument which measures the total effect over the duration of the whole storm. That is the possibility of opposite effects cancelling each other out and giving an average which is mathematically correct but misleading. To take an extreme case, a storm might start with rain coming from the North with rain at say 30° from the vertical,



Plate 6.1. The 3-gauge instrument for determining angle of inclination and direction of rainfall.

then swing suddenly as the storm centre passed overhead to an equal amount of rain, at the same angle, but from the South. The total vector for the whole storm would be vertical and might be construed as meaning that the rain fell vertically. A comparison of the catch of inclined and horizontal gauges will give some measure of the extent to which this phenomenon has occurred during the storm, but a full quantitative evaluation of the changes during the storm would require either the simultaneous recording of rates of rainfall from each of the three inclined gauges or detailed analysis using continuous recordings of wind speed and direction. Either would be a major meteorological investigation outside the scope of the present study.

6.4. RESULTS OF WIND EFFECT MEASUREMENTS.

The three-gauge instrument was in operation at Henderson Research Station during the whole of the 1959/60 and 1960/61 rainfall seasons, and the inclination and direction were computed for all rains except those of less than 0.05 inches which are of no significance in relation to run-off and erosion. The results of two seasons warrant only tentative conclusions about rainfall patterns as a whole, and any inference which may have significance to agriculturalists or meteorologists should be subjected to further investigation. The suggested inferences drawn from these results are by-products of the main purpose which was to record wind effects in order to better interpret the other simultaneous measurements of rainfall characteristics.

6.4.1. Angle of Inclination.

From casual observations during the previous six rainy seasons it was predicted that the angle of inclination would be substantially less than in the case of the non-convective rain previously reported. Table 6.1. and Fig. 6.2. show that this is the case. Only in one rain out of 113 was the composite storm vector at more than 45° from the vertical, and only one other storm fell in the range $40^{\circ} - 45^{\circ}$. It is therefore unlikely that the results are influenced by the limitation that the analysis is only valid for angles up to 45° . Small storms of less than 0.25 inches show little pattern in the distribution among groups of specified values of θ , as shown in Table 6.1. and Fig. 6.2. The remaining storms, i.e. those greater than 0.25 inches, show a negative correlation between quantity and angle of inclination θ , that is the bigger falls are associated with more nearly vertical rain. For all rains of more than 0.25 inches this correlation is significant at the 4%

TABLE 6.1. ANGLE OF INCLINATION OF FALLING RAIN.

Angle of Inclination with Vertical (degrees)	Falls of Less than 0.25 ins.		Falls greater than 0.25 ins.		Falls greater than 0.50 ins.		Totals for 1959/60 & 1960/61		Percentage of total in each group.
	Number	Amount	Number	Amount	Number	Amount	Number	Amount	
0 - 5	9	1.18	11	10.02	6	8.05	20	11.20	18.1
5 - 10	7	1.43	21	22.74	14	20.15	28	24.17	39.1
10 - 15	4	.35	11	8.54	4	5.45	15	8.89	14.4
15 - 20	6	.73	13	6.30	3	2.56	19	7.03	11.4
20 - 25	6	.80	5	2.63	3	1.93	11	3.43	5.6
25 - 30	1	.19	3	2.01	2	1.74	4	2.20	3.6
30 - 35	4	.33	3	1.62	2	1.21	7	1.95	3.1
35 - 40	5	.40	2	1.61	2	1.30	7	2.01	3.3
40 - 45	-	-	1	.86	1	.86	1	.86	1.4

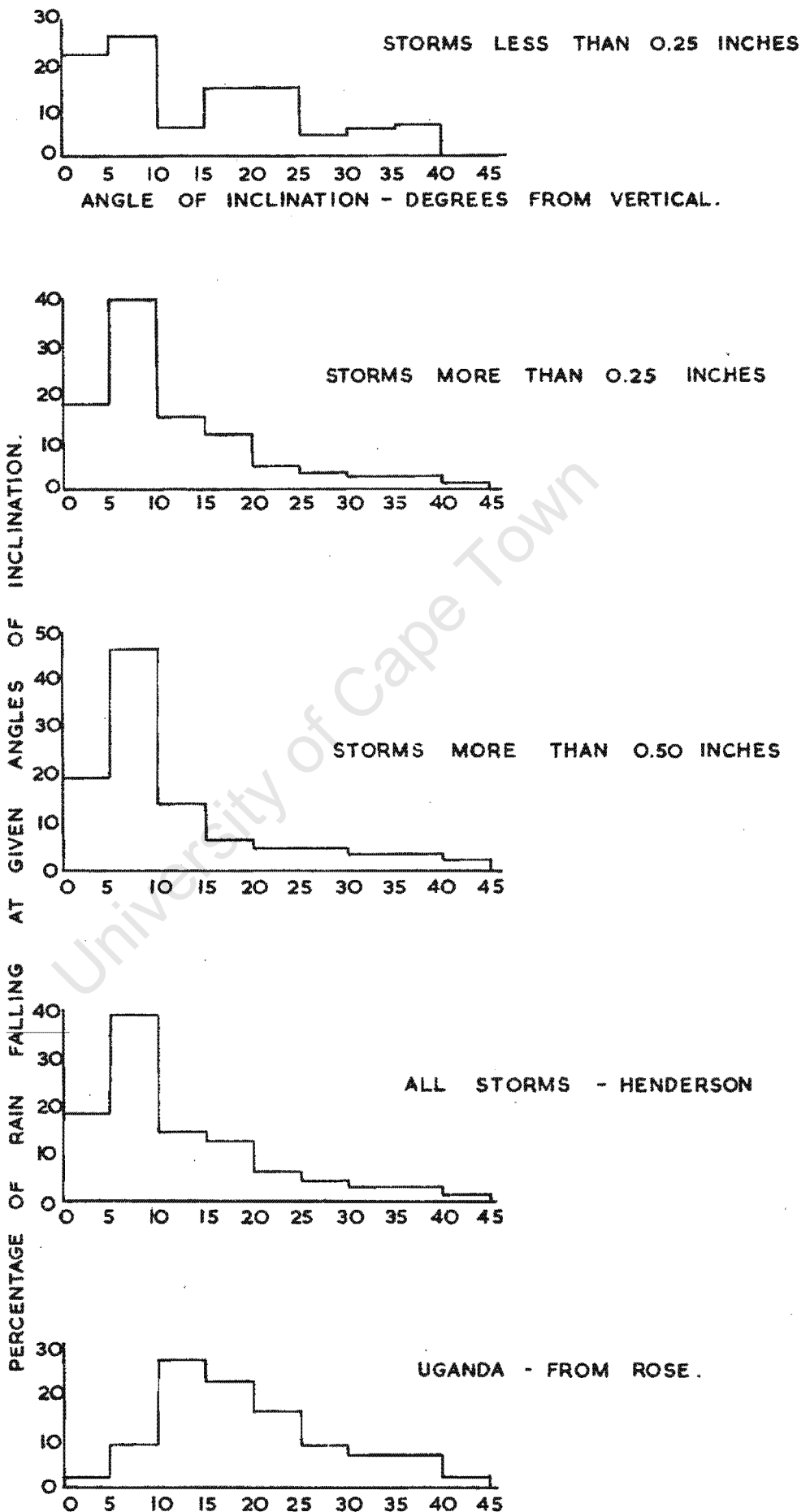


FIG. 6.2. ANGLE OF INCLINATION OF FALLING RAIN

level, and when only rains of more than 0.50 inches are included the correlation is increased, and is significant at the 2% level. The possibility of opposite effects being cancelled out by changes during the storm will increase with the duration of the storm, and so some portion of this correlation may be inherent to the instrument.

Bearing in mind these limitations of the instrument, and that the analysis covers only two seasons, the indications are that

- 1) θ seldom exceeds 45° .
- 2) For light rains (up to 0.25 inches) values of θ are distributed through the range $0 - 40^\circ$ with little pattern or regularity.
- 3) For medium rains (0.25 to 0.50 inches) the heavier storms are associated with the smaller values of θ .
- 4) For heavy rains (more than 0.50 inches) this association is stronger.

These results may be compared with those of Rose, also shown in Fig. 6.2., which were also obtained in tropical thunderstorm rain, but at an altitude of 3,800 feet in Uganda. There it was also found that very few falls occurred with θ more than 45° , but 90 percent of the total rain was deflected more than 10° . At Henderson only 43 per cent fell with θ more than 10° .

6.4.2. Direction of Rain.

The quantity of rainfall arriving at ground level from 30° sectors of azimuth are shown in Fig. 6.3. Three-quarters of the total lies in the arc between 045° and 195° . This does not necessarily mean that this is the prevailing direction from which rain bearing clouds come, because the local winds at ground surface below a thunderstorm are influenced by topography and the position of the observer relative to the centre of the storm. Since the inclination of rainfall is, in general, small it is unlikely that this concentration of direction will cause erosion to vary according to the geographical aspect of experimental plots. Although Free found that this was the case in New York, the conditions were very different in that 25% of the storms had θ greater than 45° , compared with less than 1% in the present experiments.

6.5. EFFECT OF WIND ON DROP DISTRIBUTION.

It is possible that wind may affect the size distribution of raindrops reaching the ground at any particular time. Large and small drops formed at the same time and place will follow different flight paths as the smaller drops are deflected more

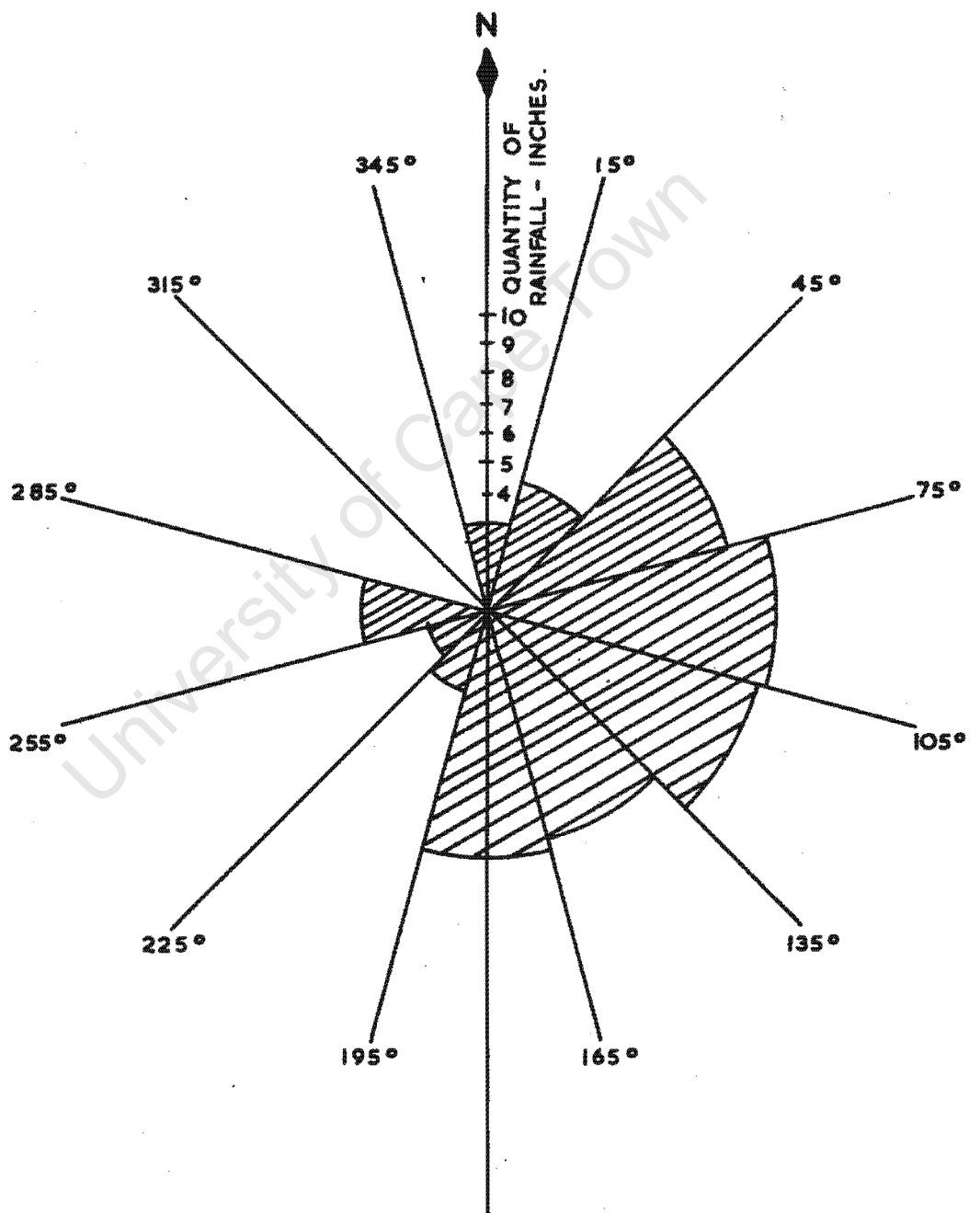


FIG.6.3. DIRECTION OF INCLINATION OF RAIN.

from the vertical, and so land farther downwind (Marshall, 157). However, the largest drops fall much faster than the smallest, and so may either arrive first (as frequently observed at the onset of thundershowers), or at the same time as smaller drops formed earlier and farther upwind, (Gunn and Marshall, 158; Rigby, Marshall and Hitschfeld, 159). Studies of the sequence of variation in drop size distribution were used by Blanchard (95) and by Atlas and Plank (111) to deduce facts about the height and time of raindrop formation. However, as it has been shown that the wind effects in Rhodesian thundershowers, as measured by angle of inclination of rain, are relatively small, the effects of wind will not be pursued when considering drop size distributions.

University of Cape Town