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Review

Rain Drop Measurement Techniques: A Review

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Received: 17 November 2015; Accepted: 4 January 2016; Published: 21 January 2016
Academic Editor: Brigitte Helmreich

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Abstract: For over a century there have been many studies that describe the use of rain drop measurement techniques. Initial manual measurement methods evolved due to improved technology to include photographic and, more recently, automated disdrometer and laser measurement techniques. Despite these numerous studies, there have been few comparative reviews of the range of methodologies, and their relative performance. This review explores the raindrop measurement techniques available, and summarizes and classifies the techniques according to the method or principle involved. The requirements of a robust raindrop measurement technique are suggested, and these are reviewed against existing rain drop measurement techniques to provide a comparative guide to the use of the range of techniques available for any research study. This review revealed that while advances in technology have allowed many of the deficiencies of early techniques to be eliminated, challenges remain in relation to the precision of the measurement of the size, shape, and velocity of rain drops.

Keywords: raindrop measurement techniques; impact and optical disdrometers; laser precipitation monitor; pluviometer

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1. Introduction

An appreciation of rain drop characteristics such as size, shape, velocity, kinetic energy, and drop size distribution is crucial for many scientific, commercial and industrial applications. Some examples of these include remote sensing, meteorology (weather prediction), telecommunications (signal distortion), and agriculture and horticulture (crop yield) radar meteorology, atmospheric physics, cloud photodetection, and measurement of tropospheric precipitation microstructure [1–3].

The characteristics of rain drops are also important for stormwater management purposes, particularly in relation to understanding how pollution wash off processes affect stormwater quality. For example, larger rain drops that possess more kinetic energy are known to result in higher pollution concentrations being washed off impervious surfaces and into downstream aquatic environments [4].

The objective of this review is to provide a summary of the development of rainfall measurements techniques, and to review and compare the different rain drop measurement techniques used in previous research studies. The scope of this review has been limited to include only those measurement techniques with the ability to measure rain drop size, shape, distribution, velocity, kinetic energy, and intensity. Different raindrop measurement techniques have been characterised according to the method used, and the relative merits of each method are discussed. In order to compare the merits of each technique, rain drop measurement methods included in this review have been broadly categorised into manual and automated techniques.

Manual rain drop measurement techniques include the stain method (measurement of stains on dyed absorbent paper), flour pellet method (measurement of rain drops that fall into finely sieved flour and produce dough pellets), and oil immersion method (measurement of rain drops in a vessel containing oil). Despite these manual methods being simple, they are time consuming, have limited measurement accuracy, and do not give real time data records. Also, these manual techniques cannot provide terminal velocity data, which is required to estimate the kinetic energy of rainfall [5]. Manual techniques are reviewed in the first part of this article.

Recent advances in technology and electronics have enabled an exploration of automated rain drop measurement techniques. These are reviewed in the second part of this article and include techniques such as the using devices to measure the displacement and mechanical energy caused by raindrops hitting a surface, optical imaging to measure the velocity, diameter, and shape of the raindrops using camera technology, acoustic techniques which measure the noise produced by rain drops hitting a diaphragm and optical scattering, whereby rain drop size, shape, velocity, and diameter are measured passing through a light or laser beam.

In the final section of this article, the essential characteristics required for an accurate rain drop measurement technique are suggested and explained. A summary and conclusions of the review are presented.

2. Manual Rain Drop Measurement Techniques

Early studies (*ca*. 1900–1960) attempted to describe rain drop size and velocity using manual measurement techniques such as chemically treated paper, and sugar or soot coated nylon screen [6–8]. These very early, functional techniques were found to provide inaccurate results, and have been superseded due to technological advancement over the last century.

2.1. Stain Method

The stain method was one of the earliest accepted techniques to be developed and it is still in use today. First described by Lowe [9], this method involves the use of chemically treated paper to measure the size of raindrops. For a short period of time rain drops are allowed to land on a sheet of absorbent paper covered with a water-soluble dye. A variety of absorbent papers have previously been used including filter paper, blotting paper, blueprint paper, paper towelling, photographic paper, and adding machine tape. Upon impact, the embedded dye reacts with the rain drops and this leaves permanent marks on the paper. The marks are then carefully measured and counted to provide information about the rain drops. One of the limitations of this method is that during prolonged sampling, the rain drop stains can overlap, which can make it difficult to accurately measure and count individual drops.

Several iterations of this method over time improved measurement accuracy, and increased size range measurement capacity including developments of the method described by Marshall and Palmer [10], and Marshall *et al*. [11] who used dyed filter paper. Two filter papers were used simultaneously to increase the accuracy of rain drop measurement. Ink blotters dusted with potassium manganese used by Anderson [12] and known water densities used by Abudi *et al.* [13], incorporated weights of raindrops to infer size. Several studies [14–22] used Whatman's No. 1 filter paper, which was identified as yielding the most accurate results.

Bowen and Davidson [23] trialled an improvement to the stain method by using a semi-automated technique which produced a continuous record of the drop size distribution. The improved method involved deflection of rain drops onto moving absorbent paper embedded with dye. The diameters of the stains were categorised into five different size classes, from which drop size distributions were calculated. A similar recording instrument in which paper tape was used to record rain drops was developed in conjunction with an equation which described drop size in relation to stain size and time lag between sampling and analysis [24–27]. Calculations resulted in a calibration chart which translated the stained area caused by rain drops into raindrop diameter [14,15]. Limitations of this methodology included the uncertainty of allowing for terminal velocity of the rain drop prior to measurement [15,28,29], and maintenance of paper temperatures, which were both found to influence stain sizes [30].

2.2. Flour Pellet Method

First developed in 1904 by Bentley [31], the flour pellet method (Figure 1) was used to study drop size distributions of rain events in Washington D.C., USA. A number of studies have since used slightly different versions of the flour pellet method to successfully analyse rainfall (Table 1).

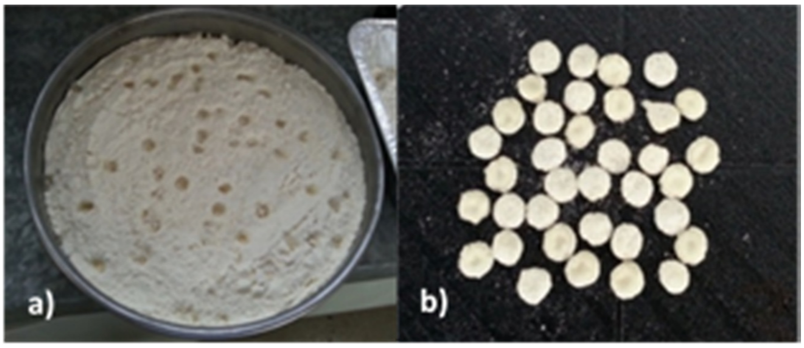

Figure 1. (**a**) Raindrop flour pellet samples collected in a pan filled with 2 cm depth of plain flour; (**b**) Flour pellets after oven drying.

Compaction of the flour over time was found to affect measured pellet size, and large sample numbers are usually required to account for the high variability in the number of rain drops observed during testing [32]. Test area should be restricted to the centre of the chosen collection tray to avoid splash effects. The test duration should also be brief (1–2 s) to avoid duplicate drop counts [4,33–39].

The chief technological advance to the flour pellet method was developed by Arnaez *et al.* [40], who used digital analysis of photographs to determine drop sizes. The main fields that still currently use the flour pellet method include soil erosion, and stormwater quality research studies [4,35,36,38–46].

Table 1. The research studies used the flour pellet method.

Research Study and Location	Purpose of Use	Method used
Laws & Parsons (1943) [47]	To measure drop sizes from natural storms	After sampling with raindrops, the formed pellets were dried in an oven. Pellets were sized with sieves and weighed. The size was calibrated by weighing dried pellets produced by drops of a known size.
Hudson (1963) [33]	To measure drop sizes from natural storms	A tray (0.05 m^2) of flour was exposed to simulated rainfall for a period of 1 s. The flour was then dried for 24 h at ambient temperature (28–30 °C) and the pellets formed were passed through a series of sieves (4.75, 3.35, 2.36, 1.18 and 0.85 mm). The pellets were then dried for 24 h at 105 °C, weighed and measured.
Kohl (1974) [32]	To verify the nozzle produced drop sizes in the rainfall simulation studies	Circular pans 21 cm in diameter and 2 cm deep were filled with flour and made level with a straight edge. After exposure to rain drops, the flour was dried (24 h at 38 °C). An 18.3 cm diameter sample was taken from the centre of the pan to avoid splash effects. The pellets were sieved (U.S. series 5 to 50 mesh) and weighed.

Table 1. *Cont.*

Research Study and Location	Purpose of Use	Method used
Carter *et al.* (1974) [48]	To study drop size distribution of natural rainfall	A circular pan (31 cm diameter) of flour (1.6 cm deep), was exposed in a rain for a short period of time. The pellets formed were first air- and later oven-dried and weighed. Raindrop diameter was estimated from the weight of the pellets.
Navas *et al.* (1990) [49]	To verify the nozzle produced drop sizes in the rainfall simulation studies	A 25.4 cm diameter plate containing an uncompacted, layer of flour (2.54 cm thick) is exposed to rainfall for 1–4 s. The small flour balls are dried for 24 h at 105 °C, and sieved (5000, 3000, 1000, 630, 500 and 250 μm) the fractions are weighed. Calibration of drops is required.
Ogunye and Boussabaine (2002) [35]	To verify the simulated drop sizes in the rainfall simulation studies	Exposure time is restricted to 1 s to minimise coalescence of the pellets in the flour. A large sample size is required to minimise the variability in counts of the rare large drops.
Arnaez *et al.* (2007) [40]	To verify the nozzle produced drop sizes in the rainfall simulation studies.	Rain drops formed small pellets in the flour that were photographed and analysed by computer.
Herngren (2005) [4]; Egodawatta (2007) [44]; Miguntanna (2009) [38]	To verify the nozzle produced drop sizes in the rainfall simulation studies.	A tray (diameter 240 mm) of uncompacted flour was exposed to simulated rainfall for a period of 2 s. Flour was dried for 12 h at 105 °C, and the pellets sieved (4.75 mm; 3.35 mm; 2.36 mm; 1.18 mm; 0.6 mm; and 0.5 mm).
Pérez-Latorre *et al.* (2010) [39]	To verify the nozzle produced drop sizes in the rainfall simulation studies.	A flour layer (1 cm depth) was placed over a surface of 50 cm × 50 cm and compacted using a ruler. The flour surface was covered to protect it from rainfall except when the cover was removed for 2 s during the simulation to collect drop samples. The diameter of pellets was measured using a calibre (±0.1 mm).
Asante (2011) [45]	To verify the nozzle produced drop sizes in the rainfall simulation studies.	A thin layer of cassava flour, and wheat flour were spread on separate trays and passed through a rain shower. The flour was dried and the pellets separated according to their size ranges using a nest of sieves. The size of raindrops was calculated from the size of pellets.
Parsakhoo *et al.* (2012) [46]	To verify the nozzle produced drop sizes in the rainfall simulation studies.	The drop impact on flour was estimated using a ruler.

2.3. Oil Immersion Method

An early manual rain drop measurement method first developed by Fuchs and Petrjanoff [50], the oil immersion method involves the collection of drops on a glass trough containing a fresh mixture of lightly viscose liquids, such as Vaseline®and light mineral oil which prevents evaporation and condensation [51–58]. Using a camera and microscope, this technique does not require calibration or special equipment [55].

The low viscosity and hydrophobic nature of the oil causes rain drops to form discreet spherical shapes, allowing drop counting and measurement by microscope [59] or via photograph [57,58,60]. Generally any low viscosity oil can be used [61], and several alternative liquids have been utilised in a range of studies, including Apiezon oil A, Shell 33, vacuum pump oil, paraffin oil and hydraulic fluid mixture, hydro carbon solvent, silicone oil, anisole mineral oil mixture, cold hexane, and grease (−20 °C) [57–60,62–67]. Courshee and Byass [59] found that the use of two oils of different densities improved drop shape measurement. Using a microscope or a photograph, they found it easier to identify the drops trapped at the liquid interface (two liquids) rather than one.

2.4. Photographic Method

The photographic method has been used extensively to measure rain drop size and velocity, and undergone many iterative improvements since its development by Mache in 1904 [68] (Table 2). Initially, Laws [69] measured drop sizes using a 9 cm × 12 cm still camera mounted behind a chopper-disc driven by a small synchronous motor (Figure 2).

Light infiltration problems have restricted some use of the photographic method to night time sampling [7,70,71]. Use of the Illinois camera resulted in drop count errors due to superimposition of multiple drops [70]. Digital pixilation also limited the accuracy of several photographic techniques [72]. In addition, photographic techniques are subject to environmental influences such as wind which may cause drop drift and measurement errors [73]. The time consuming nature of some experimental photographic techniques were found to limit their practical use [74].

Table 2. Range of photographic methods used in rainfall measurements studies.

Research Study	Methodology and other Comments
Abudi *et al.* (2012) [13]	A Motion-Scope® PCI-8oosc camera (Redlake Imaging Corp., San Diego, CA, USA) was used in conjunction with special software capture falling drops. Calibration of images resulted in drop velocity and size measurement.
De Jong (2010) [73]	A Canon Powershot® camera (Canon Inc., Tokyo, Japan) was with a Stopshot® module (Cognisys Inc., Traverse City, MI, USA) which triggered two successive flashes. The process was activated by an infrared sensor passed by a raindrop drop. Drop images were captured twice allowing velocity measurement (Figure 3).
Salvador *et al.* (2009) [72]	Low shutter speeds result in drops appearing as cylinders in a photograph. Drop diameter and velocity were calculated based on the selected shutter speed.
Sudheera and Panda (2000) [75]	High resolution photographs were digitised using a scanner. A digital single lens reflex (SLR) camera produced digital images converted by a CCD (charge couple device) camera connected to a MVP/AT computer system. Pixel aggregation was used to partition images to allow drop size and count measurement.
Cruvinel *et al.*, & Cruvinel *et al.* (1996, 1999) [58,61]	A Sony® TR50BR handycam video (Sony, Minato, Tokyo) and a MATROX® PIP-640B (Matrox, QC, Canada) were used in conjunction with oil immersion to calculate drop sizes.
Eigel and Moore & Kincaid *et al.* (1983, 1996) [57,76]	Drops were photographed using a 35 mm Fujichrome® 100 (Fujifilm, Tokyo, Japan) and illuminated with a circular fluorescent light. Slides projected on a screen resulting in a 30:1 magnification, supporting small drop measurement (0.1 mm diameter).
Mueller (1966) [77], Jones (1959) [78], Jones and Dean (1953) [79], Jones (1956) [80]	An Illinois camera was used to capture raindrops in an area of 1 m^3 of air every 10 s. This involved two synchronised cameras at perpendicular angles. The three-dimensional image of the shape of the raindrops was then calculated. The accuracy of this method was limited to >0.5 mm in drop size [81].
Laws (1941) [69]	A still camera was used mounted behind a chopper-disk driven by a small synchronous motor (Figure 2). A collimating lens resulted in accurate drop size measurement. Dark field illumination and the chopper-disk made it possible to obtain multiple images of a drop on a single film.

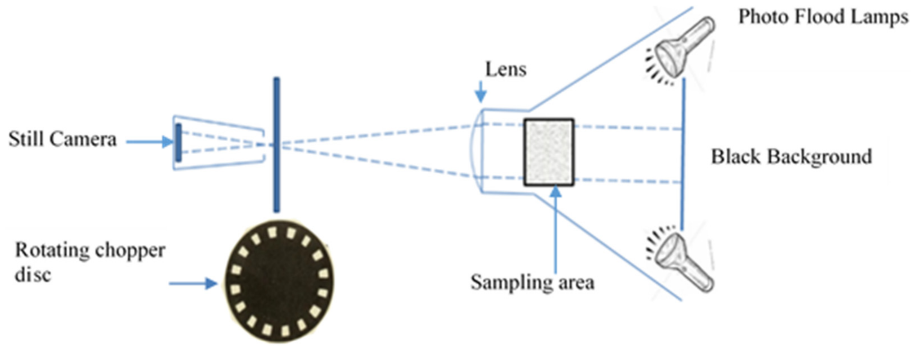

Figure 2. Schematic still camera setup developed to measure the velocity of falling drops [68].

Figure 3. Vaisala Rain Cap disdrometer (Vaisala, Vantaa, Finland)[82].

3. Automated Rain Drop Measurement Techniques

3.1. Impact Disdrometers

The kinetic energy of rain drops is critical to soil erosion and stormwater pollutant wash off studies because it is indicative of the potential of drops to displace particles normally bound to a surface, causing to soil particles to enter surface water flows. The combination of drop size distribution and drop velocity can provide an estimation of kinetic energy, however there have been several previous attempts to take measurements directly [83–85]. This has been done using either acoustic or displacement methods.

3.1.1. Acoustic Disdrometers

Acoustic disdrometers involve the generation and recording of an electric signal via a piezoelectric sensor when drops fall on a specialized diaphragm. Based on the relationship between kinetic energy and drop size calculations [53,69], this electrical signal is converted to kinetic energy via the measured acoustic energy [73,83–95].

Modifications to the sensors used in acoustic disdrometers by Nystuen *et al.* [96] enabled use in marine environments, however difficulties remained during high rainfall intensity measurement. Jayawardena and Rezaur [83] also successfully modified the acoustic disdrometers, and improved drop size distribution, rain intensity and kinetic energy measurement accuracy. Other commercial devices have been successfully developed by Salmi and Ikonen [97], Salmi and Elomaa [84], Winder and Paulson [86], Bagree [98] and Vaisala [82] (Figure 3).

Limitations to accuracy in drop size estimation arise using acoustic disdrometers due to the difficulty in obtaining a uniform acoustic response over the entire diaphragm. Difficulties in the accurate measurement of smaller drop sizes also remain because of insensitive diaphragms, and splash effects. In addition, higher intensity storms are not able to be measured due to background noise which decreases measurement accuracy.

3.1.2. Displacement Disdrometers

Energy generated by drops falling on the top surface of a displacement disdrometer is translated via magnetic induction, and converted via electrical pulse to estimate the size of a rain drop (Figure 4).

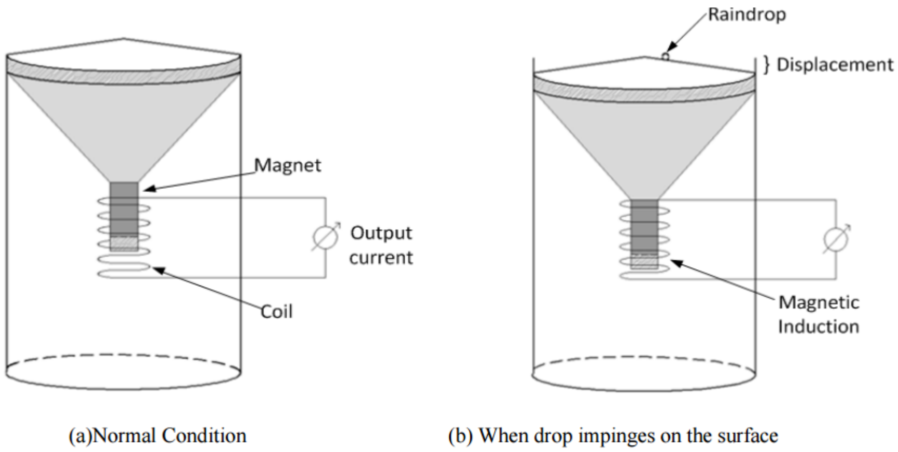

Figure 4. Schematic of the principle of operation of displacement disdrometers [98].

In addition to magnetic induction, several mechanisms have previously been trialled to accurately measure drop size including elastic springs [98], bonded strain gauges [99], and pressure transducers [84,100–103]. Arguably the most widely used displacement disdrometer is the Joss-Waldvogel Disdrometer [85] (Figure 5) which has been commercially available for past 45 years. This unit has undergone several iterations to improve the composition of the cone which is the principle measurement component. Successful modifications have included the addition of a digital converter [104–106] (Table 3). Although this disdrometer may have provided advantages such as measurement over a wide range of drop sizes, and the ability to continuously sample over longer durations, limitations remain including accurate drop counting, and accurate measurement of velocity, kinetic energy, intensity, and drop shape.

Figure 5. Joss-Waldvogel impact disdrometer (Distromet Ltd., Basel, Switzerland) [106].

Table 3. Capability summary of a range of optical disdrometers.

Device Name	Study	Rainfall Intensity	Drop Size	Fall Speed	Kinetic Energy	Sampling Area (Thickness of Light Beam)
Thies Clima® Laser Precipitation Monitor (LPM) (Adolf Thies GmbH & Co. KG, Göttingen, Germany)	Bloemink & Lanzinger (2005) [107]; Clima (2007) [108]; Upton &Brawn (2008) [109]; Anderson (2009) [110]; de Moraes Frasson (2011) [111]	<250 mm/h	<8.5 mm	<11 m/s	Not Measurable	45.6 cm^2 (22.5 cm × 2 cm)
OTT Parsivel® disdrometer (OTT Hydromet, Loveland, Colorado, USA)	Krajewski *et al.* (2006) [112]; Thurai *et al.* (2009) [113]; Friedrich *et al.* (2013) [114]	<1200 mm/h	0.2–5 mm	0.2–20 m/s	<30 KJ	54 cm^2 (18 cm × 3 cm)
Particulate Measurement System (PMS) 2DG spectrometer (Particle Measuring Systems, Airport Blvd Boulder, Colorado, USA)	Hawke (2003) [115]	Not Measurable	0.15–9.6 mm (in 64, 0.15 mm size categories)	<25 m/s	Measurable	100 mm^2
Paired-pulse optical disdrometer (P-POD)	Grossklaus *et al.* (1998) [116]	Not Measurable	0.35–6.4 mm	Measurable	Not Measurable	Cylindrical volume with 120 mm length and 22 mm diameter
Particle Measuring System GBPP-100S	Solomon *et al.* (1991) [117]	Measurable	0.2–13 mm in 0.2 mm increments	Measurable	Not Measurable	13 × 500 mm^2
Paired pulse optical disdrometer (P-POD)	Illingworth and Stevens (1987) [118]	Not Measurable	0.72–3.62 mm in 0.21 mm steps, <0.72 and >3.62 mm also detectable	Measurable	Not Measurable	Measurable
VIDIAZ spectro Pluvio meter	Donnadieu (1980) [119]	Not Measurable	>0.6 mm	Measurable	Not Measurable	80 cm^2
Optical spectro pluviometer (OSP)	Picca &Trouilhet (1964) [120], Donnadieu *et al.* (1969) [121], Klaus (1977) [122], Hauser *et al.* (1984) [123], Salles & Poesen (1999) [124]; Salles *et al.* (1999) [125]	<35 mm/h underestimates intensity by 12%. >35 mm/h, underestimates intensity by 38%.	0.3–4.7 mm (±6%) (Larger drops are detected but without quantification of their diameter)	0.2–10 m/s	Not Measurable	Not reported

3.2. Optical Disdrometers

Optical technologies (optical imaging or optical scattering) are non-intrusive rain drop measurement techniques. These methods do not influence drop behaviour during measurement, and have successfully resolved drop break up, and drop splatter problems experienced by other measurement methods [126,127].

3.2.1. Optical Imaging

Recent imaging techniques developed have involved two motion cameras (2DVD) to show raindrop microstructure, including front and side drop contours, fall velocity, drop cant and horizontal velocity. General rainfall parameters such as rain intensity and drop size distributions have also been accurately measured [128]. Two motion cameras record images of drops which have been used to accurately measure drop velocity, diameter, and shape (including oblateness, Figure 6). Measurement errors arising from drop drift caused by the tall unit design have led to design modifications, including the development of an indoor model [129], and one specifically designed for outdoor use [127].

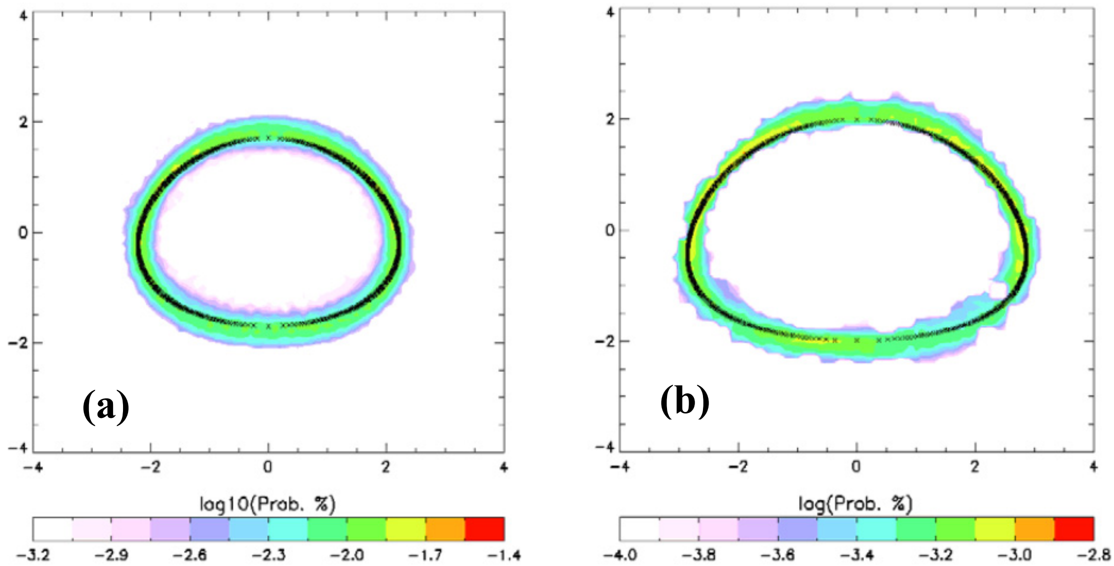

Figure 6. Drop shapes in terms of probability of (**a**) 4 mm and (**b**) 5 mm obtained from 2DVD [113].

Liu *et al.* [130] developed a video system capable of accurate drop shape and velocity measurement (Figure 7). The set up consists of optical and processing units, and a unique imaging unit comprised of a planar array charge-coupled device (CCD) sensor. The shape, size, and velocity of drops can be accurately measured by a single CCD sensor.

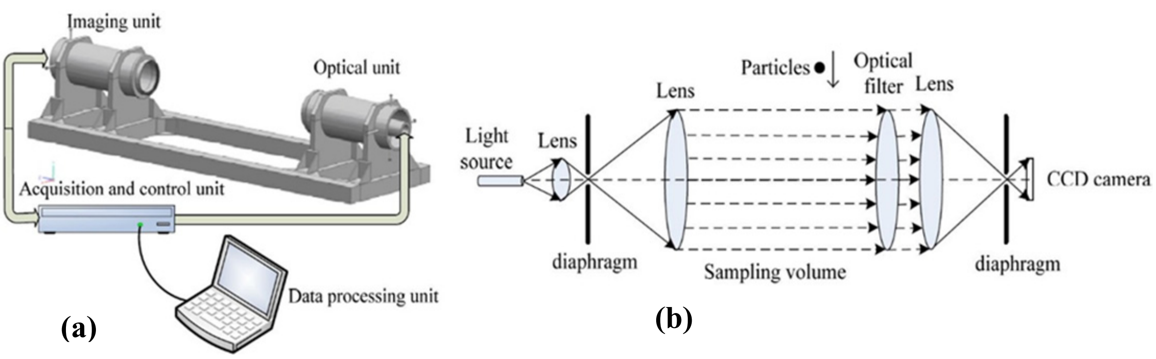

Figure 7. (**a**) Video setup; (**b**) Schematic of imaging process [129].

3.2.2. Optical Scattering

Optical scattering techniques involve the generation of a horizontal light beam which travels to a receiver where electrical measurements are taken. Drops that pass through the light beam cause the light to scatter. The attenuation of the light caused by each drop is converted to an electrical pulse by the receiver which is then successfully converted to accurate drop velocity measurement [108] (Figure 8).

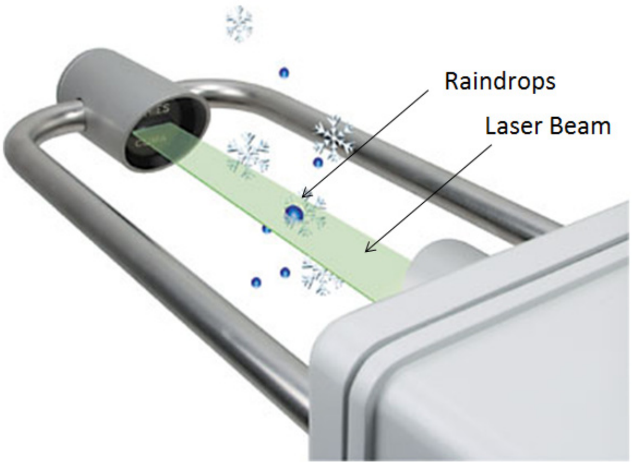

Figure 8. Schematic of optical disdrometer [108].

Since the mid-20th century, optical disdrometers have been used to successfully count and size individual rain drops [114,119–123,131–134] (Table 4). Performance evaluations have suggested that optical disdrometers may be limited to measuring larger drop sizes and that the rainfall intensity measurements were inaccurate [9,124]. Although optical disdrometers have also been found to be sensitive to wind effects [116], a modified version [118] included a paired pulse and was successfully used in windy conditions (wind speeds up to 20 m/s). Several models are also capable of successfully differentiating between solids and liquids, enabling use in the snow [135,136].

Table 4. Summary of the Characteristics of Rain Droplet Measurement Techniques.

	Stain Method	FPM	Oil Immersion Technique	Photography Technique	JWD RD 80 & RD 69 Disdrometer	VR—WXT520 Disdrometer	2 Dimensional Video Disdrometer	OTT Parsivel Disdrometer	Laser Optical Disdrometer
Principle	Manual	Manual	Manual	Optical Technology	Impact Displacement Technology	Impact Acoustic Technology	Optical Technology	Optical Laser Technology	Optical Laser Technology
Measurability of larger drops	2.0 mm	5 mm	2.1 mm	Not reported	5.0–5.5 mm	5.0 mm	Yes Range not reported	5.0–5.5 mm	8.5 mm
Measurability of smaller drops	0.3 mm	0.75 mm	Not reported	Not reported	1.0 mm	0.8 mm	Yes Range not reported	0.2 mm	0.125 mm
Measurability of counting the number of droplets	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes
Measurability of the rain fall velocity	No	No	No	Yes	No	No	Yes	20 m/s	11 m/s
Measurability of the rain kinetic energy	No	No	No	No	No	No	No	Yes up to 30 kJ	No
Measurability of the rain intensity	No	No	No	No	No	No	Yes	Yes	Yes
Ability to account the oblateness	No	No	No	No	No	No	Yes	No	No
Ability to sampling continuously for longer durations	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Resilience to the wind effects	No	No	No	No	No	No	No	No	No
*** Resolution**					127 classes	8 classes		1014 (32 size × 32 velocity)	430 classes (23 × 20)
Temporal resolution					1 min	1 min		10 s to 60 min	1 min

* The resolution is defined as the number of classes into which the drops can be classified.

4. Characteristics of a Robust Rainfall Droplet Measurement Technique

For a realistic prediction and monitoring of droplet characteristics, a robust rainfall measurement instrument must be able to:

- Measure both larger (up to 10 mm) and smaller (down to 0.3 mm) drop sizes precisely;
- Count the drop sizes accurately;
- Measure the fall velocity precisely;
- Measure the rainfall intensities across all expected ranges;
- Sample continuously; and
- Tolerate wind effects while retaining drop measurement precision.

The possibility of achieving these target characteristics using the full range of available techniques is discussed below.

4.1. Precise Measurement of Larger Rain Drops

Because larger rain drops (>6 mm) are correlated with larger pollution wash off from urban areas [110], their accurate measurement is essential to stormwater quality studies that utilise rainfall simulation. Accurate manual rain drop measurement is limited to a maximum of approximately 2 mm in diameter due to splashing effects distorting results [7,17,137]. Large size drops are often overestimated due to the drop size growth over time on absorbent paper during use of the stain method [138]. The flour pellet method is limited to measurement of drops larger than about 0.5 mm due to sieve size limitations [5]. The measurement of larger drops using the oil immersion method is limited to 2.1 mm diameter due to drop splatter and amalgamation of drops [7,53,59].

Automated measurement techniques such as the impact disdrometers are also limited to the measurement of drops less than 5.5 mm because of a reliance on calculations using the relationship between velocity-diameter which plateaus beyond this diameter range using current formulae [53,113,139]. Although the two dimensional video and laser particle methods claim to have the capacity to precisely measure drop sizes as large as 10 mm, peer reviewed studies to confirm this are yet to be published.

4.2. Precise Measurement of Smaller Rain Drops

The accurate measurement of small raindrops is challenging using both manual and automated techniques. Manual raindrop measurement techniques are restricted to precise measurement of drops of greater than 0.3 mm diameter [15,33,44,59,61,66,140]. Automated measurement techniques are also restricted to measurement of drops greater than 1 mm in size [141].

Several studies reported difficulties in relation to impact disdrometers and the measurement of smaller raindrop diameters [85,134,142,143]. Intense rainfall causes splashing and vibrations is also reported to distort the measurement of smaller drop sizes [142,144,145]. Measurement accuracy difficulties caused by laser technology recovery time (dead time error), and noise distortion that affect the measurement of smaller drop sizes are known to restrict precise measurement to 1 mm effects [145–148].

Acoustic disdrometers have limitations arising from the duration of the decaying waveform which when measured leads to distorted results [94,149]. Optical disdrometers claim to measure smaller drops with more precision, however, the reliability of these measurements remains unreported.

4.3. Accurate Measurement of the Number of Rain drops

Accurate measurement of the number of drops is critical for the generation of a drop size distribution for any given rainfall event. This is the most widely used characteristic used to describe rainfall [150,151]. Manual measurement techniques have a good capacity to accurately count drop numbers over short durations. Automated disdrometers such as laser precipitation monitors have the capacity to accurately sample over the longer durations required by rainfall sampling studies. However, limitations on the measurement accuracy of drops below 0.2 mm remain due to drop splatter [152] and background noise [112]. Optical disdrometers claim to accurately count drop numbers, however, the reliability of these measurements has also not been verified or reported.

4.4. Precise Measurement of Rain Drop Velocity

Manual techniques are not capable of measuring drop velocity with an adequate level of precision [153]. Although limited to static measurements, and defined by frame capture rate per second, photographic techniques are capable of precise drop velocity measurement. Video technique measurement (2DVD), laser precipitation monitors, and optical spectral pluviometers can also provide precise, continuous drop velocity measurements.

4.5. Ability to Measure a Wide Range of Rainfall Intensities

Because of the particular features of each technique, none of the manual rain drop measurement techniques, nor the impact disdrometer methods are capable of measuring rainfall intensity reliably. Although overestimation of higher rainfall intensities (>20 mm/h) is common, optical laser and video (2DVD) measurement of rainfall intensity are generally accepted as more accurate [154]. Due to the limitations regarding accurate measurement of high rainfall intensities, it is recommended that optical laser techniques are used in combination with a conventional pluviometer to enable measurements to be verified and to ensure accurate rain intensity measurement.

4.6. Precise Measurement of Rain Drop Shape (Oblateness)

Initially spherical due to surface tension forces, with increasing size, fall velocity and drag forces, rain drops tend to flatten out at the base, and sometimes develop a concave shape (Figure 6). The degree of oblateness may affect the kinetic energy of the drop, and thus the potential wash-off process caused by drop impact. Efforts to precisely measure the oblateness of larger drops have been limited, and it has been suggested that as yet, it may not be accurately described [155].

4.7. Capacity to Accurately Sample Rainfall over a Long Duration

Restricted sampling durations are synonymous with manual raindrop measurement techniques [156,157]. Automated disdrometers (laser, optical, acoustic, and impact) are known to measure rain drops in real time with virtually no time duration limitation. However, as discussed above, the accuracy of these devices can be limited.

4.8. Capacity to Perform Precise Rain Drop Measurement during Adverse wind Conditions

Because sampling time is usually quite brief, all of the manual measurement techniques are known to be accurate (within their individual output limitations) during windy conditions. Air movement and wind noise around automated samplers (disdrometers, video, and acoustic) are known to influence rain drop trajectory and sound filtering, which have been shown to lead to inaccuracies in drop size measurements in previous studies [86,152,158]. Wind effects were reduced to an acceptable level in one previous study by tilting an acoustic disdrometer parallel to wind direction [114]. However, this does not offer a reliable or permanent solution.

5. Summary and Conclusion

Every rainfall measurement technique has strengths and weaknesses and these generally result in some limitation in the accuracy of rain drop characteristic measurements. The precise requirements of any proposed study will determine the most appropriate method or combination of methods that should be used to produce the most suitable and accurate raindrop measurements. This is particularly the case for stormwater management purposes, particularly in relation to understanding how different raindrop characteristics affect pollution wash off processes and how this influences stormwater runoff quality from urban areas.

The main findings of this review have been:

- The use of manual rain drop measurement techniques have been successfully used in studies involving drop size measurements. However, these methods are generally not suitable for the measurement of smaller and larger drop sizes outside the normal range (0.3–6 mm), they are not capable of precise drop counts, they are not suitable for continuous rainfall monitoring studies, and they are less effective during intense and windy storm conditions. In addition, manual rain drop measurement techniques cannot be used to measure or report drop velocity.
- Automated (impact and optical) disdrometers are generally able to sample continuously over long durations. However, inaccuracies in drop size and velocity measurements are likely during heavy rain. It is recommended that optical disdrometers should be used in combination with a conventional rain gauge to enable validation of results and ensure precise rain intensity measurement.

The common limitations of all the rain drop measurement techniques includes their inability to precisely measure both the smaller, and the larger drop sizes outside the normal size range, their inaccuracy during high intensity rainfall events, and their reduced measurement precision during windy conditions. With improvements in technology occurring on a nearly daily basis, it is anticipated that the accuracy and precision of automated rainfall measurement techniques will significantly improve in the near future. This will enable more precise measurements to be undertaken and result in a much better understanding of real rainfall characteristics.

Author Contributions: All three authors contributed equally to this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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