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Rain Gauge Data Quality May Hinder Confident Detection of Secular Changes in Rainfall Rates – A Key Aspect of the Evolving Global Water Cycle

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Rain Gauge Data Quality May Hinder Confident Detection of Secular Changes in Rainfall Rates—A Key Aspect of the Evolving Global Water Cycle

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Abstract

There is a wide diversity of methods by which rainfall arrival at the surface of the Earth can be measured and recorded. Among these are methods that provide extensive spatial geographical coverage, including radar-based, satellite-based, and other remotely-sensed approaches. However, these rely on assessments of their accuracy that rely on more direct observation at the surface. Rain gauges remain the dominant tool for point observations. Secular changes in rainfall arrival are of great potential significance in the study of the terrestrial water cycle, notably possible intensification at various timescales - daily, hourly, and particularly sub-hourly. Intensification may result in changes to the magnitude of surface runoff relative to initial losses or to infiltration, with consequent effects on urban flash flooding and related hazards. It is argued here that there are both well-known and little-known limitations to gauge data, that bear in particular on the confident detection of secular changes in short-term rainfall intensities, and in the correct identification of trends toward increasing intensity or declining intensity, both of which have been identified in published studies of regional secular rainfall change. This paper seeks to highlight some of these important data quality issues arising from the collection of 'ground-truth' point rainfall observations.

Keywords: secular change; hydrologic cycle; rainfall; rain gauge data quality

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1. Introduction

Quantifying the fluxes in the global water cycle has become more challenging owing to apparent secular changes in a range of influential variables, including global temperatures, atmospheric humidity and cloud characteristics, global wind speeds, rainfall rates, and others. The apparent secular changes are at least in part anthropogenically-caused, and linked to changes in greenhouse gas composition of the atmosphere. However, other drivers are also involved, including altered landsurface characteristics, particularly related to agricultural and forestry activity, river regulation and irrigation, and the growth of large urban centres, including mega-cities (Wu et al. 2024 [1], Nerantzaki et al. 2025 [2]). There are linked ocean changes also, including in the tides and ocean stratification (Bij de Vaate et al. 2022 [3], Opel et al. 2024 [4]), seasonal extent of sea ice (Muskett 2011 [5]) and in the vigour of the thermohaline circulation and global sensible heat transport (Gleckler et al. 2006 [6]).

Among this spatio-temporally complex set of issues, each bringing challenges for measurement and monitoring, is that of the observation and recording of precipitation. To limit the scope of the present article, discussion is limited to rainfall over land, and precipitation over the oceans, as well as snowfall and cryosphere processes, are excluded.

Rainfall over land constitutes one of the major fluxes in the global water cycle. Measurement and quantification are made challenging by the complex spatio-temporal variability in rainfall arrival. The challenges are increased further by the current non-stationarity of many characteristics of rainfall arrival arising from the secular changes in rainfall characteristics including frequency, depth, and intensity. Studies of secular rainfall change have a substantial history, exemplified by the early work of Kraus (1955) [7], but are becoming increasingly necessary. For example, Sreenath et al. (2022) [8] presented evidence that rainfall over the western coast of India is becoming less stratiform in character and increasingly convective. More generally, secular changes in aspects of rainfall arrival including seasonal distribution, rainfall intensity, and duration of rainfalls have all been foreshadowed in models of future climate scenarios (Moustakis et al. 2021 [9], Li et al. 2025 [10]).

Contemporary observational data are important for attempts to quantify and understand secular rainfall change, and for validating climate models. Moreover, some aspects of rainfall arrival have importance because of the societal and economic costs that can arise from events such as flash floods in major cities and urban areas (Dallan et al. 2024 [11], Guerreiro et al. 2024 [12]). In relation to urban environments, possible increases in sub-daily and sub-hourly rainfall intensity are of concern because of the increased flash flood hazard that they may bring. Intense rainfalls, such as those from thunderstorms, may fall over limited spatial scales and may be short-lived. These characteristics lie generally beyond the capacity of satellite precipitation data, and indeed pose particular problems for the establishment of networks of suitable rainfall observing stations at the ground. Moreover, global data on sub-daily precipitation are generally scarce, and comparable sets of sub-hourly gauge data are extremely scarce (Guerreiro et al. 2024 [12]).

The present paper therefore seeks to highlight some challenging aspects of the collection of rainfall data needed for the confident detection of secular change, particularly in rainfall intensity. There are multiple drivers of secular rainfall change, some of which are climatic in origin and others that arise from other causes. Distinguishing the climate signal in rainfall data therefore requires a knowledge of other influential factors. A key objective here is to highlight in addition a number of instrumental limitations arising from rain gauges that bear on the gathering of accurate rainfall data. The focus will be primarily on the most widely-deployed type of gauge, the tipping-bucket rainfall gauge (TBRG). Four key aspects of TBRG performance will be discussed in the context of secular rainfall change:

1. ability to record intense, short-term rainfall depth and intensity accurately;
2. ability to record low- to moderately intense rainfall depth and intensity accurately;
3. ability to record rainfall duration accurately;
4. influence of changes made through time in gauge hardware or gauge exposure on detection of secular rainfall change.

We begin with a brief commentary on secular changes in rainfall intensity. Discussion then considers the arrival of rain over large urban centres, which can be prone to hazardous flash flooding linked to short-duration, intense rainfalls, and the challenges of quantifying its various characteristics. This will serve to introduce some key issues that are then explored in more detail as they relate to station data more generally.

2. Secular Changes in Rainfall Intensity

Rainfall intensities are considered to be sensitive to rising temperatures owing to the increased moisture-holding capacity of warmer air. The potential to hold more moisture increases at about 7% per °C according to the Clausius-Clapeyron (CC) relation (Moustakis et al. 2020 [13]). However, multiple instances of departures that differ from this expected relationship have been reported (Ali and Mishra 2017 [14]). Ivanic and Shaw (2016) [15] for instance showed > CC scaling at many locations in the USA. Moisture availability may limit moisture transfer to the atmosphere, and lead to sub-CC scaling, which has been reported from several drier areas (Ali and Mishra 2017 [14], Xu et al. 2024 [16]), including semi-arid Sicily (Pumo et al. 2019) [17]. Dew point temperatures may therefore account for the scaling more effectively than air temperatures. Da Silva and Haerter (2025) [18] have shown that an increase in the frequency of occurrence of convective (rather than stratiform) rain can by itself account for apparent > CC scaling, and that when considered separately, both forms of precipitation may individually follow the expected CC relation.

There appear to be regional differences not only in the CC scaling of rainfall intensities, but also in the direction of secular change in rainfall intensities. Fu and Wu (2024) [19] for instance recorded that in the global tropics, there was evidence that low-intensity rainfalls were intensifying whilst higher-intensity falls were declining in intensity. Morrison et al. (2019) [20] had earlier employed an ensemble of climate models to conclude that the greatest changes to sub-daily rainfall extremes were likely to arise in the tropics. The scope of the present paper does not allow for further examination of regional variation in secular rainfall change. However, it is sufficient to note that there is evidence for regionally diverse patterns of secular change in rainfall intensity, including both the direction and rate of change. The amount of precipitation recorded at particular intensities also depends on the frequency of occurrence of those intensities. Some studies suggest that secular changes in the frequency of occurrence may contribute more to change in total precipitation than do increases in intensity (Myhre et al. 2019) [21].

We turn now to consider large urban centres, which can be particularly sensitive to increases in rainfall intensity. Additional drivers of rainfall change occur in such areas, including abundant aerosols, urban warmth, and the effects of high-rise buildings, making the identification of climate-related secular change more difficult. Moreover, in large urban centres collecting data at ground observing stations faces particular challenges.

3. Rainfall Over Large Urban Centres

Large urban centres provide a useful example of the challenges facing confident detection of climate-related secular rainfall change. Given that in many countries, the population is to a large extent located in urban centres (Li et al. 2021) [22] with the urbanised area progressively increasing (Zhao et al. 2022) [23], the possible intensification of rainfall linked to increased moisture-holding capacity of a warmer atmosphere (particularly over the urban warmth of mega-cities, where updrafts can entrain moisture (Cha et al. 2023) [24] looms as a very important variable linked to the urban flood hazard, and particularly to urban and peri-urban flash flooding. More intense rain also has implications for the triggering of pollution events, such as the overflow of sewage systems (Gurerreiro et al. 2024) [12]. Particularly in relation to large urban centres, there is concern with the tendency for short-term (sub-daily and sub-hourly) rainfall intensities to increase more than for daily or longer integration times (Ayat et al. 2022) [25]. Deng et al. (2024) [26] showed for instance that in the Pearl River Delta (China), hourly extreme intensities were increasing 134% more rapidly than daily extreme intensities. It has been suggested that urban areas may strengthen the tendency to intensification of local rainfall and rainfall both within and beyond the urban area itself (Li et al. 2023 [27], Yan et al. 2024 [28], Singh et al. 2024 [29], Torelló-Sentelles et al. 2024 [30]). Dallan et al. (2024) [11] applied high-resolution convection-permitting climate models to future climate scenarios for northern Italy, which supports about half the Italian population. Considering 20-year return periods, Dallan et al. (2024) [11] reported predicted intensification for 2090 – 2099 (their 'far future' scenario) of 27% for 1 hour durations, and only 18% for 24 hour durations. They highlighted the risk posed to increasing hazards including flooding, debris flows, and others.

An alternative approach is to consider the total amount of precipitation delivered to urban centres by rain of different intensities, which reflects the combined effects of intensity and frequency of occurrence, as mentioned earlier. For instance, Xiong et al. (2025) [31] reported on a study of rainfall in major global urban areas, based on Global Precipitation Measurement (GPM) data, having found station gauge data too limited. For the period 2001 – 2023, they reported that rainfall from drizzle (0.1 – 0.5 mm h^{-1}) and light precipitation (0.5 – 2.5 mm h^{-1}) had increased in 77% and 68% of urban areas respectively. In contrast, moderate (2.5 – 10.0 mm h^{-1}) and heavy (≥ 10 mm h^{-1}) precipitation had increased in only 42% and 38% of urban areas. Xiong et al. (2025) [31] noted that expanded gauge networks will be required to elucidate more precisely the changes in rainfall that are driven by large urban areas.

In addition to their effects on rainfall in the city and surroundings, urban and peri-urban areas, owing often to extensive impervious surfaces accompanied by efficient systems for conveying storm runoff, are particularly sensitive to flooding caused by short-term, intense rainfalls. Contributing factors include the effect of urban roughness elements such as high-rise buildings in slowing the movement of rain cells or fronts across the urban area. Buildings themselves can also provide a barrier against which wind-driven rain (WDR), falling obliquely, can lead to runoff from exposed building surfaces. Such runoff can quickly drain to the ground, and this effect, which increases with wind speed and the consequent deflection of rain droplet trajectories, has been shown to be capable of increasing runoff ratios in areas having high-rise buildings with large wall areas (Gao et al. 2021) [32]. Walls create little initial loss into surface depression storage. Flash flooding from rapid rain runoff occurs in many large cities, including Melbourne, Australia (Jamali et al. 2018) [33] and Barcelona, Spain (Barrera et al. 2005) [34], and an increasing hazard can result from the growth of the urban area (Faccini et al. 2018 [35], Idowu and Zhou 2023 [36]), as well as from changes in the rainfall regime of the local climate. Cities perturb local and regional rainfall via various other mechanisms, including altered aerosol abundance, urban warmth and reduced albedo, and the effects can extend over tens of kilometres from the city centre (Liu & Niyogi 2019 [37], Lalonde et al. 2023 [38]). A range of other hazards can in turn be linked to increasing urban rainfalls and/or rainfall intensities, including economic disruption, as well as physical consequences including landslides, debris flows, and other forms of rapid mass movement (Kaiser and Akter 2025) [39].

Studies of urban hydrology have suggested that especially for small catchments, rainfall data need to be collected with temporal resolutions measured in minutes, in order to provide sufficient resolution to understand the flash flooding process (Lyu et al. 2018 [40], Yang et al. 2016 [41]). Convective cells can reach their peak intensity in 15 min (Keat et al. 2018) [42]. Others have found lower temporal rainfall resolution of up to 1 h acceptable (Li et al. 2022) [43]. In the case of thunderstorm cells affecting limited areas (and often with short lifetimes), high spatial resolution is also needed (Hu et al. 2024) [44].

3.1. Some Challenges Facing the Recording Rainfall Arrival and Its Secular Change in Urban Centres

To decipher secular changes in urban rainfall, there are two key requirements: first, to gather data from ground stations or other sources that provide sufficient spatial and temporal resolution, and second, to understand the effects of the urban areas themselves as distinct from changes in the local climate system.

Many sources of potentially suitable ground- or near-ground level rainfall data have been proposed, including the attenuation of links between mobile telephone towers (Lian et al. 2022) [45], the speed of car windscreen wipers (Bartos et al. 2019) [46], and video or acoustic data collected by security cameras (Zheng et al. 2023 [47], Wang et al. 2024 [48]). Security cameras offer the potential to provide a very large network of possible rainfall recording sites. Dunkerley (2023) [49] provided a review of a wide range of available methods for the measurement of rainfall intensity. Crowd-sourced data gathered by residents with their own rain gauges may provide another pathway to data with sufficient spatial and temporal resolution (Khaing Kyaw et al. 2024) [50]. Many of the indirect methods of observation, such as the video and acoustic methods, or microwave attenuation, require calibration against a more direct measure of rainfall, and rain gauges currently provide the only real option. Often, this is provided by point observations collected with standard meteorological gauges of some kind (termed 'meteorological point rainfall'). The most commonly-deployed device is the tipping-bucket rain gauge (TBRG). Though a seemingly simple device, the TBRG, like many rainfall gauges, is prone to multiple sources of error, some of which are widely-known, whilst some others are relatively neglected. Moreover, for urban areas, some special adaptations of rainfall measurement are needed. Recording the amount of wind-driven rain (WDR) striking the obstacle presented by the side of a building, for instance, is often carried out using flat-plate wall gauges that catch the water draining from a defined small area of wall, and feed it through a drain hose to a measuring device such as a TBRG or to a measuring vessel. Such gauges were illustrated by Blocken and Carmeliat (2004) [51] (refer particularly to their Figures 6 and 7) and photos can be seen in Wang et al. (2020) [52], Cho et al. (2020) [53], and others. The vertically-projected area of a wall is effectively zero, and so in the absence of wind, almost no rain should strike a wall. In contrast, under windy conditions, rain droplets falling toward the ground are deflected and wall gauges collect significant amounts of wind-driven rain (WDR).

Wind deflection of falling rain poses one of the challenges to ground-based rainfall measurement. Wind speeds are known to be locally higher above a gauge, and to reduce the collection of droplets by more than 10% in a wind of 7 m s^{-1} (Cai et al. 2025) [54]. In addition, when droplets arrive obliquely to the collecting funnel of a rain gauge, the effective collecting area of the gauge orifice is less than the area applicable to rain falling vertically though still air. Wind and hence droplet trajectories can become complex among tall buildings, where eddies can develop (Gholamalipour et al. 2022) [55]. A particular problem can arise if such a gauge is out-of-level, a situation that is known to be quite common. In that case, the effective collecting area of the gauge can be reduced if the device is tilted off-level. Evidently, the conditions in cities with extensive high-rise buildings pose challenges for the reliable measurement of rainfall. As city populations expand, the morphology of cities changes, and building heights increase, the changing influences on rainfall and rainfall measurement, such as a strengthened urban heat island and changed wind eddying and other conditions, would be compounded with those of secular climate change. The difficulty of unravelling these influences in station data is substantial, but given the hazard of flash flooding in many urban areas, tracking and quantifying any secular changes in climate-related rainfall intensity is necessary to support preparedness and the knowledge to forecast future flood hazards.

An additional aspect of rainfall arrival that requires consideration is the sequence of intensities during a storm event. Convective events often develop their highest intensities relatively early in the event duration (Berti et al. 2020) [56]. This has been referred to as "front loading" (Ghanghas et al. 2024) [57]. Storms with more uniform intra-storm intensity may yield smaller runoff peaks and reduced flash flood hazard. Identifying the distribution of intensity during a rainfall event again highlights the need for sufficient temporal resolution in rainfall data, especially when there may be secular change in the distribution of intra-storm intensities. This may be associated with an increase in the frequency of convective rainfall events.

4. Wind-Driven Rain in Non-Urban Areas

Even at open sites away from tall buildings, such as the open sites preferred for conventional meteorological rain gauge ground stations, challenges to the reliable measurement and reporting of rainfall do occur, including those relating to wind deflection of rain just mentioned. TBRGs record the rain volume, or equivalently, the depth of rain, caught by the vertically-projected area of the collecting funnel. However, if the rain arrives obliquely owing to wind, then the amount caught may be less than when the rain arrival is vertical, because the effective collecting area is reduced (Sharon 1980) [58]. Rinehart (1983) [59] reported that a gauge that was off-level by 2° would incur an error of 9% in a wind of 10 m s^{-1}. Knowing only the volume caught by a TBRG, and in the absence of data on the angle of arrival of wind-driven rain, the intensity (rain depth divided by the collection time interval) would be interpreted as being lower than the value which would be felt by a hillside facing the oblique rain arrival (or the wall of a building). The effective intensity on sloping sites can be calculated if wind speed or direct measurements of rain inclination are available. The problem of off-level rain gauges when exposed to WDR occurs even in areas away from major urban centres. From a sample of gauges, Rinehart (1983) [59] reported a mean tilt of 2.3° and a maximum tilt of 6.7°.

The perturbing influence of wind is significant, because in many areas globally, rain accompanied by wind is common. The global trade winds, which occupy almost half the global surface (Hastenrath 1991, 139) [60], bring rain with strong onshore winds at many coastal locations. Thunderstorms also frequently bring rain with gusty outflow owing to the strong downdrafts (e.g. Choi 2001) [61]. Sharon (1980) [58] reported typical rain inclination (measured from the vertical) of 40 – 60° in mid-latitudes, owing to wind deflection of rain droplets. Aldridge (1975) [62] observed wind-driven rain at Arahura on the west coast of the New Zealand South Island, and reported that only 7.4% of the total rainfall fell vertically, again owing to exposure to strong onshore winds.

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Likewise, Chand & Bhatgava (2005) [63] reported frequent wind-driven rain at exposed locations across India. Qi et al. (2023) [64] showed that heavy rain in coastal areas of China tended to be associated with strong winds.

To derive the most reliable rainfall intensity data, with which to quantify any secular change, it is therefore important to know whether changes in local wind speeds might themselves have undergone change, and account for some component of any change in actual rainfall intensity and/or in gauge catch efficiency. Zeng et al. (2019) [65] reported that although 'global stilling' of terrestrial winds had been detected since about the 1980s, the trend to reduced wind speed had reversed in about 2010, and speeds had been increasing once again since then (refer to Fig. 1 in Zheng et al. 2019 [65]). Increasing wind speeds globally were confirmed by Zhang et al. (2024) [66]. These wind changes may well affect rain gauge catch, and may continue to do so in coming decades if wind speeds continue to change. By reducing gauge catch, increasing wind speeds could result in some fraction of a true secular increase in rainfall intensity being offset by the instrumental error. Furthermore, Zha et al. (2021) [67] and Martinez and Iglesias (2024) [68] concluded that under future climates, there is likely to be a geographically complex pattern of changes in wind. Zha et al. (2021) [67] for instance proposed that under global warming scenarios, near-surface wind speeds in the Northern Hemisphere will decline whilst those in the Southern Hemisphere will increase. Diversity in wind change may further hinder the confident detection of secular change in rainfall intensity owing to differing effects on gauge performance. This suggest that wind data providing sufficient temporal resolution may also be needed. Changes in landuse in areas surrounding rainfall observing sites, such as urban or suburban development, agroforestry, or clearing of trees, may also have effects on rain gauge performance that could be confounded with actual secular changes in rainfall. Large-scale removal of deep-rooted native vegetation to develop agricultural or pastoral land for instance may have considerable effects on the rainfall climate. An example can be seen in the wheat belt lands of Western Australia, where winter rainfall is argued to have decreased by ~ 20% (along with reduced cloud cover and other effects) since extensive clearing of native eucalyptus trees that began around 1950 (Lyons et al. 1993) [69].

5. Limitations of Station Data as Evidence of Secular Change in the Water Cycle

Having discussed urban and peri-urban areas where rainfall intensity and possible secular changes in intensity can be critically important, we can now consider some of the further difficulties that arise more generally when reliance is placed on TBRG or similar data to record rainfall arrival.

The tipping bucket rain gauge (TBRG) is considered to have originated with the work of Wren and Hooke in the 18th century (Biswas 1967) [70]. This type of gauge was originally intended to allow the tallying the depth of rainfall arriving progressively during the day, rather than reliance on single daily readings. There was at that time likely to have been little concern with accurately recording rainfall over timescales of minutes, and no concern with short-term intensities is apparent in the historical accounts. Therefore, in attempting to use TBRG data to study secular changes in short-term rainfall rates, the TBRG is really being applied to collect data for which it was not originally designed. We consider next some of the ongoing limitations of TBRGs that are widely relied on to provide rainfall amount and rainfall rate data, and additionally to provide 'ground-truth' data against which indirect methods of rainfall measurement can be calibrated and validated.

5.1. Filling Time and Timing of Bucket Tip Events

It is widely considered that the time taken to fill and tip a single tipping bucket provides the highest time resolution possible in TBRG data (Wang et al. 2008 [71], Dunkerley 2024 [72]). The intensity during the seconds or minutes taken to fill a bucket is estimated by assuming that the rain fell at a constant rate during the filling time. The shorter the time elapsed between successive tip events (the inter-tip time or ITT), the higher is the derived estimate of the rainfall intensity. Each successive ITT provides a separate estimate of the rainfall intensity.

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Whilst this is a useful approach, the achievable accuracy depends on the precision with which the ITT is logged at the ground observing station. In intense rain, the small buckets forming the mechanism of a TBRG (which typically have a capacity of 5 – 7 mL) can fill and tip rapidly. For a typical TBRG sensitivity of 0.2 mm of rainfall and a collecting area of ~ 323 cm^2, the filling time for a single bucket at 100 mm h^{-1} is ~ 7.2 s. At 150 mm h^{-1}, this falls to 4.8 s. Evidently, therefore, the data logging system used needs to be capable of sub-second resolution when time-stamping bucket tip events during intense rainfall. However, commonly-used event data loggers only provide 1 s resolution, which means that a tip time such as 4.8 s cannot be accurately recorded. This issue was explored by Dunkerley (2025) [73], who showed that owing to limited logger resolution, and the rounding of recorded times to the nearest whole second, tip times can be logged as too brief or too long. Further, when the tip time itself is recorded with insufficient accuracy, then intensity estimates can be biased. For example, if a tip occurred close to 4.5 s after the previous tip (ITT = ~4.5 s, giving an intensity of ~ 160 mm h^{-1}), this might be logged as 4.0 s (apparently intensity 180 mm h^{-1}, which is 12.5% too high) or as 5.0 s (apparent intensity 144 mm h^{-1}, or 20% too low). None of this was likely to have been of concern to Wren and Hooke devising a means to record rainfall in the 18th century, but intensity errors of 10% – 20% have become relevant today. This is a contemporary problem, and one that is relatively easily reduced by adopting higher time resolution in data recording. Estimating intensity correctly, especially high intensity rain of the kind that triggers flash flooding, is critical if secular change in rainfall arrival is to be detected correctly. There are gauges available that do not suffer from the discretisation arising from bucket-filling times. These include weighing gauges that can offer much higher resolution data on the rate at which rain water accumulates, since the weight can be recorded at shorter time intervals (Colli et al. 2013) [74]. However, these gauges are more complex and costly than TBRGs, and are not as widely deployed.

5.2. Measurement Bias Affecting TBRG Data at High and at Low Intensities

TBRGs can under-report rainfall at moderate- to high-intensities. This effect is well-known. It arises primarily because once a bucket has filled, overbalanced, and begun to empty, rain water can continue to fall into the bucket from the gauge collecting funnel. This can happen at many successive tips, but the additional water is not reflected in a larger total number of tip events; the total recorded rainfall consequently can be too small by a margin that can be 20% – 30% or more (Duchon et al. 2014) [75]. Zheng et al. (2023) [76] reported errors of up to 34.1% and Sypka (2019) [77] of up to 37.5%. Table 1 presents the data from eight published studies, and shows that in several cases the under-reporting is listed as arising at intensities > 50 mm h^{-1}. In order to document and correct for this effect, which varies among TBRGs of different designs, dynamic calibration needs to be undertaken at a range of intensities, ideally spanning the range expected at a location where the gauge would be deployed (Stransky et al. 2007) [78]. Suitable calibration and/or post-processing of data can allow the under-reporting bias to be greatly reduced.

Table 1. Published estimates of under-reporting errors in tipping-bucket rain gauges.

under-reporting error	range of intensities	source
up to 10%	> 50 mm h^{-1}	Goormans and Willems (2008) [79]
> 5%	140 – 240 mm h^{-1}	Colli et al. (2019) [80]
> 15%	200 mm h^{-1}	Luyckx and Berlamont (2012) [81]
20%	120 mm h^{-1}	Stransky et al. (2007) [78]
20% > 30%	120 mm h^{-1} 240 mm h^{-1}	Vasvari (2005) [82]

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8.8%	175.2 mm h^{-1}	Duchon et al. (2014) [75]
5 – 29%	> 50 mm h^{-1}	Humphrey et al. (1997) [83]
10 – 15%	> 200 mm h^{-1}	Molini et al. (2005) [84]

It has been reported in a number of studies that TBRGs may in addition tend to exhibit an opposite bias, and over-report rainfall at low- to moderate-intensities. This effect is less well-known and relatively little studied. Table 2 lists seven published studies that have quantified the extent of over-reporting. These studies show that the effect may be seen at intensities below about 50 mm h^{-1} (which is actually quite intense rain) and may have a magnitude of the rainfall depth error of more than 20%.

Table 2. Published estimates of over-reporting errors in tipping-bucket rain gauges.

over-reporting error	range of intensities	source
up to 22%	≤ 30 mm h^{-1}	Vasvari (2005) [82]
6.6%	22 mm h^{-1}	Stransky et al. (2007) [78]
2.8%	50 mm h^{-1}	Shedekar et al. (2009) [85]
> 20%	mostly 30 – 50 mm h^{-1}	Lanza and Stagi (2009) [86]
15%	25 mm h^{-1}	Gorman (2011) [87]
8%	low intensities	Colli et al. (2013) [74]
up to 11.1%	≤ 30 mm h^{-1}	Zheng et al. (2023) [76]

Several factors may contribute to over-reporting, including inappropriate calibration at an intensity higher than generally occurs at the field site where the gauge is deployed. Another mechanism that has been suggested is the retention of some water in an emptying bucket, as a result of surface tension. Marsalek (1981) [88] estimated that the volume retained in a bucket after it had tipped could lie in the range 0.15 – 0.5 mL, though further accurate data on this seem to be lacking. A volume of 0.5 mL amounts to ~ 7 – 8% of the volume of a typical TBRG bucket, so that for an incompletely emptied bucket, less additional water is needed to trigger the next tip event. This bias could arise during many successive tips. Like under-reporting at high intensities, this was probably not of concern in the 18th C, but today could lead to over-estimates of the rainfall depth during some integration time (hour, day) and hence to over-estimation of intensity. Therefore, for optimal operation, TBRG buckets should be manufactured from a hydrophobic material. Hydrophobic plastics (polyethylene, polypropylene, etc.) are suitable. These materials have a typical contact angle of ~100 degrees. In contrast, gold is often used to plate brass TBRG buckets, presumably in an attempt to reduce corrosion. However, gold is classified as hydrophilic, having a contact angle of ~ 60 degrees. It may therefore inhibit complete bucket emptying. Nevertheless it is claimed that gold plating ensures that no water remains in a tipped bucket (see for example documentation for the Environdata RG50 TBRG https://www.environdata.com.au/weather-sensors/tipping-bucket-rain-gauge, consulted 30 June 20225). Teflon would be a suitable material to reduce water adhesion by surface tension, and from the start of 2020, Hyquest Solutions has produced TBRG buckets made of polymer containing Teflon (https://hydrometproducts.kisters.eu/fileadmin/NEWS/Flyer/BucketAssembly_TBRG.pdf, consulted 30 June 2025). If such devices are progressively adopted at rainfall observing sites as older devices require replacement, then a shift in recorded rainfall depths and intensities seems likely to occur. This effect could be confounded with actual secular change in rainfall arrival.

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5.3. Possible Bias in Apparent Rainfall Durations in TBRG Data

As noted above, accurate recording of rainfall depth during any integration time (15 min, 1 h, 1 day) is required so that the mean rainfall rate can be estimated with confidence. However, it is also necessary to know the duration of rainfall, so that rainfall rate (mm h^{-1}) can be estimated as depth (mm) / duration (h). It cannot be arbitrarily assumed that rain was continuous during a period of observation, especially during intervals of an hour or more (Schleiss 2018 [89], Dunkerley 2019 [90]). For example, if during a rain hour, rain actually fell during only 50 minutes, and not for the entire hour, then the mean rainfall rate during the rain would have been higher than would be suggested by dividing the hourly rainfall depth by 60 minutes. The bias would be an under-estimate of mean rainfall rate by 20%. Clearly, therefore, we need both accurate rainfall depth and rainfall duration data. In the case of the latter, TBRGs are affected by the time required to fill a bucket, before any rain can be recorded. Thus, the onset of rain may be recorded at a time after the true moment when rain began. A similar rain duration error can occur at the end of rain also, because a bucket might be almost full and about to tip when rain ends. Thus, the previous tip would be the only marker for the apparent cessation of rainfall. Both timing uncertainties tend to under-estimate rainfall duration, and hence to result in over-estimates of rainfall rate. A challenging issue here is that acquiring data on true rain duration becomes more difficult in locations where there is marked intermittency. Intermittency can involve more than 20 cessations and re-commencements of rain in one day (Dunkerley 2019) [90]. Moreover, of course, secular rainfall change might involve a change in the extent of intermittency, with effects on apparent rainfall rate unless true rainfall duration data were available.

6. Discussion

The foregoing review has sought to touch on a number of issues that may affect the recording of rainfall by TBRGs, or the interpretation that might be placed on TBRG data that suggest that a secular change in rainfall arrival has occurred. The objective has been to show that there are indeed multiple situations in which other causes might account for apparent changes in rainfall. These include aspects of gauge behaviour, including changed catch related to changes in wind exposure that might themselves be related to changes in the local or regional landscape or environment, or changes in intermittency and rainfall duration, or changes in the fabrication of TBRGs designed to reduce the problem of incomplete bucket emptying caused by surface tension effects. It is important to remember that any systematic departure from the nominal 0.2 mm per tip event typical of TBRGs can affect hundreds of tip events in a single day or hour, such that the cumulative absolute depth error can grow in size. It is also important to emphasise that the uncertainty in tip timing described earlier is most problematic in intense rain, because it is then that the tip times are measured in seconds. It was noted above that many data loggers deployed with TBRGs provide a timing resolution of only 1 s, and therefore cannot accurately record inter-tip times in intense rainfall. Once again, the can lead to errors in intensity when deduced from inter-tip times. A shift to data loggers that provide better timing resolution might again lead to apparent changes in peak storm rainfall intensities that might not reflect actual secular changes in rainfall arrival. This suggests that it will be necessary to archive pertinent meta-data describing the site and equipment used along with rainfall data.

What does all of this mean for the identification of true secular changes in rainfall arrival? There are several possible pathways to reduced uncertainty. One is the wider adoption of more modern methods of recording rainfall arrival, a number of which are now available. Acoustic methods provide an example. In these methods, the impact of individual rain drops is detected using a microphone housed in a suitable weatherproof but resonant housing. The arrival of the first drop can often then be identified and timed with confidence, and similarly the cessation of rain can be identified unambiguously, in a way not possible with a TBRG. Example data from an installation where an acoustic rainfall recording system was co-located with a conventional TBRG were presented by Dunkerley (2020) [91]. Other forms of rain gauge provide greater sensitivity in the recording of

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intensity, including weighing gauges (Hanson et al. 2001) [92]. However, any change in the hardware used to record rainfall is likely to result in apparent changes in rainfall arrival when compared with data collected with different apparatus in previous years or decades. Therefore, being aware of these possible instrumental effects may drive a move to deploy new devices in parallel with existing devices for a significant period, so that instrumental effects on the rainfall data might be detectable. It is hoped that this brief review might help to promote such initiatives, as well as the archiving of the necessary meta-data.

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