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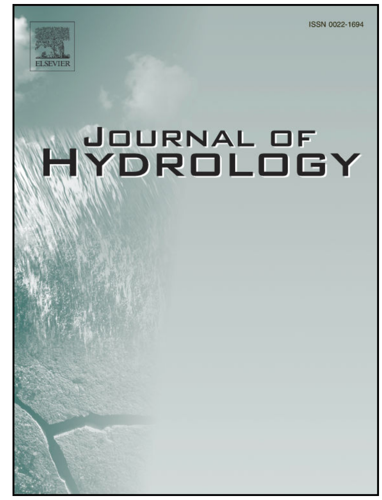

Technical Note

The history of rainfall data time-resolution in a wide variety of geographical areas

Renato Morbidelli, Amanda Penelope García-Marín, Abdullah Al Mamun, Rahman Mohammad Atiqur, José Luís Ayuso-Muñoz, Mohamed Bachir Taouti, Piotr Baranowski, Gianni Bellocchi, Claudia Sangüesa-Pool, Brett Bennett, Byambaa Oyunmunkh, Brunella Bonaccorso, Luca Brocca, Tommaso Caloiero, Enrica Caporali, Domenico Caracciolo, M. Carmen Casas-Castillo, Carlos G.Catalini, Mohamed Chettih, A.F.M. Kamal Chowdhury, Rezaul Chowdhury, Corrado Corradini, Jeffrey Custò, Jacopo Dari, Nazzareno Diodato, Nolan Doesken, Alexandru Dumitrescu, Javier Estévez, Alessia Flammini, Hayley J.Fowler, Gabriele Freni, Francesco Fusto, Leoncio García-Barrón, Ancuta Manea, Sven Goenster-Jordan, Stuart Hinson, Ewa Kanecka-Geszke, Kanak Kanti Kar, Wiesława Kasperska-Wołowicz, Miina Krabbi, Jaromir Krzyszczak, Alba Llabrés-Brustenga, José L.J. Ledesma, Tie Liu, Marco Lompi, Loredana Marsico, Giuseppe Mascaro, Tommaso Moramarco, Noah Newman, Alina Orzan, Matteo Pampaloni, Roberto Pizarro-Tapia, Antonio Puentes Torres, Md Mamunur Rashid, Raúl Rodríguez-Solà, Marcelo Sepulveda Manzor, Krzysztof Siwek, Arturo Sousa, P.V. Timbadiya, Tymvios Filippos, Marina Georgiana Vilcea, Francesca Viterbo, Chulsang Yoo, Marcelo Zeri, Georgios Zittis, Carla Saltalippi

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The history of rainfall data time-resolution in a wide variety of geographical areas

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Abstract

Collected rainfall records by gauges lead to key forcings in most hydrological studies. Depending on sensor type and recording systems, such data are characterized by different time-resolutions (or temporal aggregations), t_a. We present an historical analysis of the time-evolution of t_a based on a large database of rain gauge networks operative in many study areas. Globally, t_a data were collected for 25,423 rain gauge stations across 32 geographic areas, with larger contributions from Australia, USA, Italy and Spain. For very old networks early recordings were manual with coarse time-resolution, typically daily or sometimes monthly. With a few exceptions, mechanical recordings on paper rolls began in the first half of the 20th century, typically with t_a of 1 h or 30 min. Digital registrations started only during the last three decades of the 20th century. This short period limits investigations that require long time-series of sub-daily rainfall data, e.g, analyses of the effects of climate change on short-duration (sub-hourly) heavy rainfall. In addition, in the areas with rainfall data characterized for many years by coarse time-resolutions, annual maximum rainfall depths of short duration can be potentially underestimated and their use would produce errors in the results of successive applications. Currently, only 50% of the stations provide useful data at any time-resolution, that practically means t_a=1 minute. However, a significant reduction of these issues can be obtained through the information content of the present database. Finally, we suggest an integration of the database by including additional rain gauge networks to enhance its usefulness particularly in a comparative analysis of the effects of climate change on extreme rainfalls of short duration available in different locations.

KEY WORDS Hydrology history, Rainfall data measurements, Rainfall time resolution

1. Introduction

Rainfall information is an essential input to hydrological modelling for predicting extreme hydrologic events, including drought (Diodato and Bellocchi, 2011) and floods (Zellou and Rahali, 2019; Wilhelm et al., 2019), and estimating the quantity and quality of surface water and groundwater resources (Diodato et al., 2017). Together with temperature, precipitation also controls the spatial variation of terrestrial ecosystem carbon exchange (e.g. Chen et al., 2013).

Ground-based radars can provide estimation of phase, quantity, and elevation of generic hydrometeors in the atmosphere (Wilson and Brandes, 1979; Austin, 1987; Fread et al., 1995; Smith et al., 1996; Seo, 1998). Satellites can provide images by visible and infrared radiation and also data by radiometers to obtain the quantity and phase of hydrometeors (Barrett and Beaumont, 1994; Sorooshian et al., 2000; Kuligowski, 2002; Turk and Miller, 2005; Joyce et al., 2011). However, only rain gauges provide direct point measurements of precipitation at the earth surface.

Direct rainfall observations can be automatically recorded or not (Strangeways, 2010): non-recording gauges generally consist of open receptacles with vertical sides, in which the depth of precipitation is determined by a graduated measuring cylinder through human observation, while recording gauges are devices that automatically record a depth of rainfall at specific time intervals (census gauges), or a volume of rain (event gauges, used for warning systems). The last category may be of weighing type, float type, tipping bucket type, and also include the newer disdrometers that can measure the drop size distribution and velocity of falling hydrometeors. A weighing type rain gauge continuously records the weight of the receiving container plus the accumulated rainfall by means of a spring mechanism or a system of balanced weights. A float type rain gauge has a chamber containing a float that rises vertically as the water level in the chamber rises. A tipping bucket rain gauge operates by means of a pair of buckets. The rainfall first fills one bucket, which overbalances, directing the flow of water into the second bucket. The flip-flop motion of the tipping buckets is transmitted to the recording device and provides very detailed measurements of rainfall amount and intensity.

When the local rainfall was recorded through human observation, a manual transcription of the accumulated amount, typically during the last 24 h, was carried out. Instead, after the introduction of automatic recordings, initially over paper rolls (e.g. Deidda et al., 2007) and then on digital supports, rainfall information at higher time-resolutions (or temporal aggregations), t_a, became possible. Therefore, rainfall data observed until now and available in the archives are characterized by different t_a, depending on both the adopted rain gauge type and technological evolution of the recording systems, as well as on the specific interest of the data manager.

Several studies have evaluated the effect of coarse time resolutions on the estimation of annual maximum rainfall depths, H_d, with assigned duration, d (Hershfield and Wilson, 1958; Hershfield, 1961; Weiss, 1964; Harihara and Tripathi, 1973; Natural Environment Research Council, 1975; Van Montfort, 1990; Huff and Angel, 1992; Faiers et al., 1994; Dwyer and Reed, 1995; Van Montfort, 1997; Young and McEnroe, 2003; Yoo et al., 2015; Papalexiou et al., 2016; Morbidelli et al., 2017; Llabrés-Brustenga et al., 2020). All these studies have found that, for durations comparable with the measurement time-resolution, the actual value of the maximum accumulations may be underestimated up to 50% (Fig. 1). Furthermore, long series of H_d always include a significant percentage of elements derived from rainfall data with coarse t_a, therefore containing underestimated values, together with a considerable percentage of H_d values obtained from continuous data (typically recorded in the last two to three decades). This problem, as well as the relocation of stations, the use of different rain gauge types with time, the change of surroundings near the rain gauge, could produce significant effects on many derived analyses, including the evaluation of rainfall depth-duration-frequency curves, nonstationary frequency analyses (Khaliq et al., 2006; Nahar et al., 2017; Vu and Mishra, 2019) and trend estimations for extreme rainfalls (Fatichi and Caporali, 2009; Mishra et al., 2009). Morbidelli et al. (2017) showed that the use of long H_d series with underestimated values can lead to rainfall depth-duration-frequency curves with errors, up to 10%, significative in hydrological practice. They highlighted that the underestimations appreciably increased when the H_d series involved only values deduced through t_a much higher than 1 minute. Further, Morbidelli et al. (2018) demonstrated that rainfall data with coarse time-resolution play an important role in the outcomes of very common statistical analyses (least-square linear trend, Mann-Kendall test, Spearman test, Sen's method) implemented to quantify the influence of climate change on intense rainfall (Iliopoulou and Koutsoyiannis, 2020). They showed a very high sensitivity of all mentioned trend evaluations to the temporal aggregation of rainfall data, especially for the H_d series with a great probability to include many values characterized by t_a/d=1. A solution to these problems can be found in Hershfield (1961), Young and McEnroe (2003), Papalexiou et al. (2016), and Morbidelli et al. (2017). For example, Morbidelli et al. (2017) suggested the correction of the underestimated H_d values by three different relationships between the average underestimation error and the ratio t_a/d.

Frequently the problem of underestimated annual maximum rainfall depths could be solved by adopting one of the methodologies available in the scientific literature, however this cannot easily be done for the analysis of heavy rainfall characterized by sub-hourly durations. In this context, it can be deduced that the time-resolution of rainfall data also influences the type of analysis that can be conducted. In fact, it is very difficult to analyze long H_d series of durations less than 1 h because, for most geographical areas, historical data with t_a=1 min are available only for the last 20 to 30 years.

An approximate but realistic estimation of the number of rain gauges operative in the entire world is in the range 150,000-250,000 (Sevruk and Klemm, 1989; New et al., 2001; Strangeways, 2007). Since in each geographical area there are networks characterized by very different histories and managed with specific interests, the time-resolution of the available rainfall data can be quite different.

The objective of this paper is to highlight the time-evolution of t_a for rainfall records collected using networks managed by country agencies or institutions in several regions of the world (henceforth called study areas). The database is a basic support to determine the stations for which the available time-series should be adapted to obtain homogeneous series with length suitable for the statistical analysis of extreme rainfalls of different duration. Consequently, the hydrological analyses performed for these stations will be characterized by minor distortions and allow to improve, at the local scale, the design of some hydraulic structures also with regard to possible effects of climate change. Furthermore, the proposed database should stimulate international cooperation in the light to identify appropriate stations for comparative investigations of the effect of climate change on short-duration heavy rainfalls at different spatial scales.

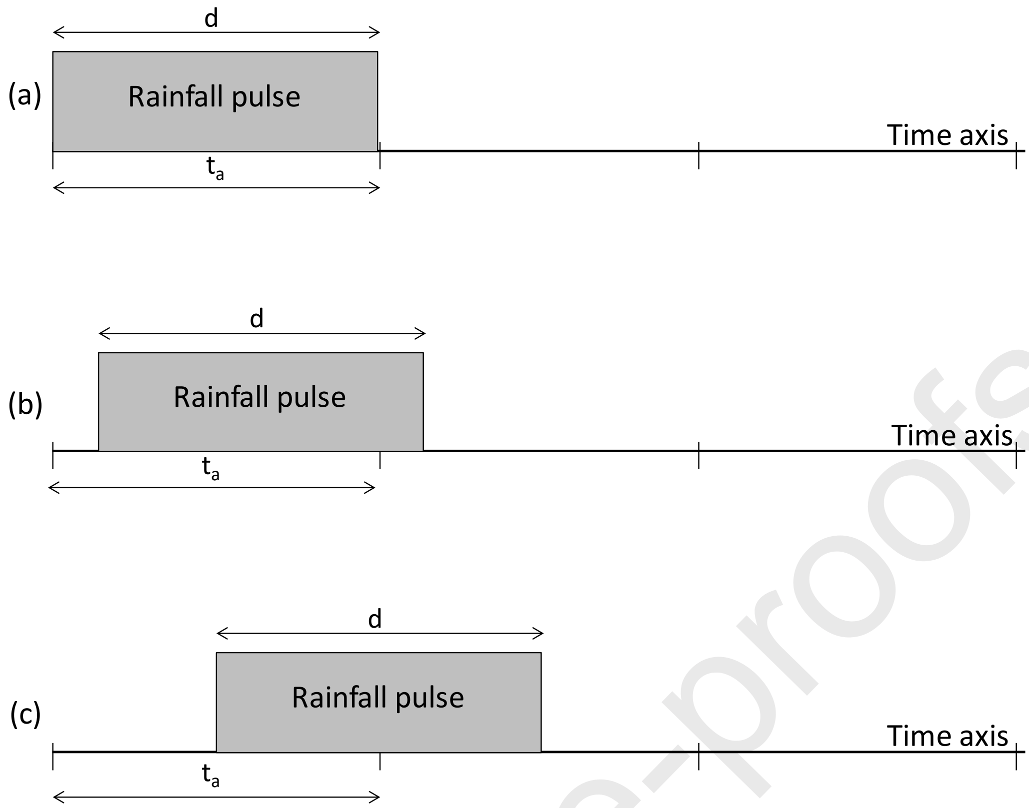


Fig. 1. Schematic representation of a rainfall pulse with duration, *d*, equal to the measurement aggregation time, t_a, of the rainfall data: (a) condition where a correct evaluation of the annual maximum rainfall rate of duration *d*, H_d, is possible; (b) condition for a generic underestimation of H_d; (c) condition for the maximum underestimation of H_d (equal to 50%).

2. Materials and Methods

2.1 Brief history of rain gauges and recording systems

Among the thousands of globally working rain gauges there are a handful of models (e.g. Helleman) which are the most frequently used with techniques developed in the late nineteenth to mid-twentieth centuries. Despite predictions that radar and satellite would make automatic and manual rain gauges measurements redundant (Kurtyka et al., 1953), they remain important, especially in regions with limited infrastructure but well developed rain gauge networks, such as Russia (Kidd et al., 2017).

Techniques for recording precipitation have been progressively improved since the onset of the scientific revolution when naturalists began to experiment with rain gauges. In 1723, James Jurin, Secretary for the Royal Society in England, called on members to submit consistent weather readings, including rainfall, to be taken once a day (Wolf, 1961). When Gilbert White collected 7 years of data in the late 1600s, his record stood as the longest in British history. By the late 1700s naturalists recognised that measuring rainfall was not simple. Heberden observed in 1769 that the height of gauge influenced the catch of rain but he mistakenly believed electricity was the cause for this variation. Research by British meteorologists Symons and William Stanley Jevons and the American Bache in the 1830s-1860s showed that the decrease in catch corresponded to wind velocity which increased proportionally as gauges moved above the ground (Kurtyka et al., 1953). Their observation that wind influences catch has been further validated by the World Meteorological Organisation (WMO) intercomparing research from the 1960s and in Goodison et al. (1998).

Modern rain gauges design and methodology emerged alongside the profession of meteorologist in the second half of the nineteenth century. George James Symons developed many of the technical and statistical methods for collecting and analysing rainfall data that informed global practice. He established the world's largest rain gauge network in Britain, totalling over 3500 stations. Symons (1869) laid out the rules for collecting rainfall that guided public works departments in the British Empire and other parts of the world. The quality of records prior to Symon's interventions were highly questionable (Anderson, 2005). He noted that prior to him: 'Indian rain gauges were taken indoors at night and locked up for safe-keeping'. Symon's guidelines advised placing the gauge one foot above the ground with a series of rain observations taken at the same time every-day (10 a.m., 1 p.m. and 4 p.m.). Symon's rain gauge provided the basis for the UK Met Office's 5-inch (127 mm) gauge and are typical of manual rain gauge construction globally (Strangeways, 2007).

Most major developments in rain gauge design and recording happened in the late nineteenth to mid-twentieth century. Automatic recording devices began to be used in the 1860s and 1870s, although manual recording remained standard for many countries and stations (such as the UK Met Office). The automatic German Hellmann syphon rain gauge, invented in 1897, was used throughout Central Europe and also in Argentina, Lithuania, Romania and Finland. As of the late 1980s, the Hellmann was the most widely used rain gauge globally with over 30,000 recorded in 2003 (Strangeways, 2003). Panama and the Philippines used the American U.S. Weather Bureau Standard. British-design gauges based on Symon's model also became popular in countries of the former British Empire, such as India.

International efforts to standardize measurements began with the foundation of the International Meteorological Organisation in 1873. The organisation lacked government funding but paved the way for the World Meteorological Organisation (WMO), established under the United Nations framework in 1950 after the signing of the World Meteorological Convention in 1947. Despite WMO efforts, significant variations within rain gauges and measurements continue to this day. As of the late twentieth century, there were over 50 different types of rain gauge being used globally (Sevruk and Klemm, l989). Every gauge type records different amounts of precipitation; this makes it difficult to systematically analyse data collected from different locations. The problem of intercomparison has been investigated by researchers working with the WMO since the 1960s, with wind loss being recognised as the most common reason for different measurements (Goodison et al., 1998; Pollock et al., 2018).

The WMO has developed a system of so-called "first class" stations which use surface synoptic observations that are collected at 3-h and daily intervals and relayed through a telecommunications network (Kidd et al., 2017). The Global Precipitation Climatology Centre, and the Global Terrestrial Network for Hydrology, both led by the WMO, offer more complete gauge data. Numerous institutions (about 180) from around the world contribute over 85,000 locations with records going back as far as 1901. Though seemingly extensive, Kidd et al. (2017) note that the total area of the world covered by rain gauges is less than half a football or soccer field (a standard field being 7140 m^2).

2.2 Rainfall data types

In all regions of the world, recorded rainfall data are characterized by different time resolutions, mainly linked to the specific objective of the network manager and also to the technologic progress of the adopted recording devices. At the current time, most rainfall amounts are continuously recorded in digital data-loggers, allowing the adoption of any aggregation time interval, even equal to 1 minute.

A few decades ago rainfall data were recorded only over paper rolls, typically with t_a=30 minutes or 1 h (see Fig. 2) even though in principle they could be characterized by an arbitrary small resolution. Finally, especially before the Second World War, most rainfall data were of daily resolution, manually recorded each day at the same local time (see Fig. 3).

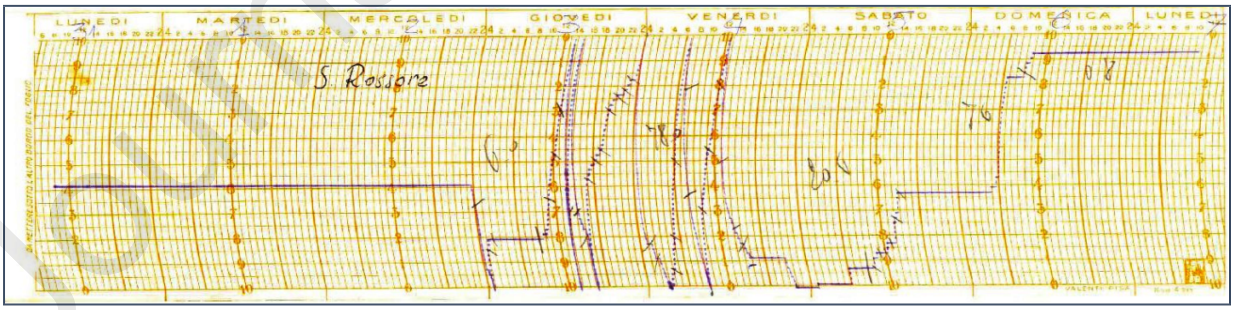
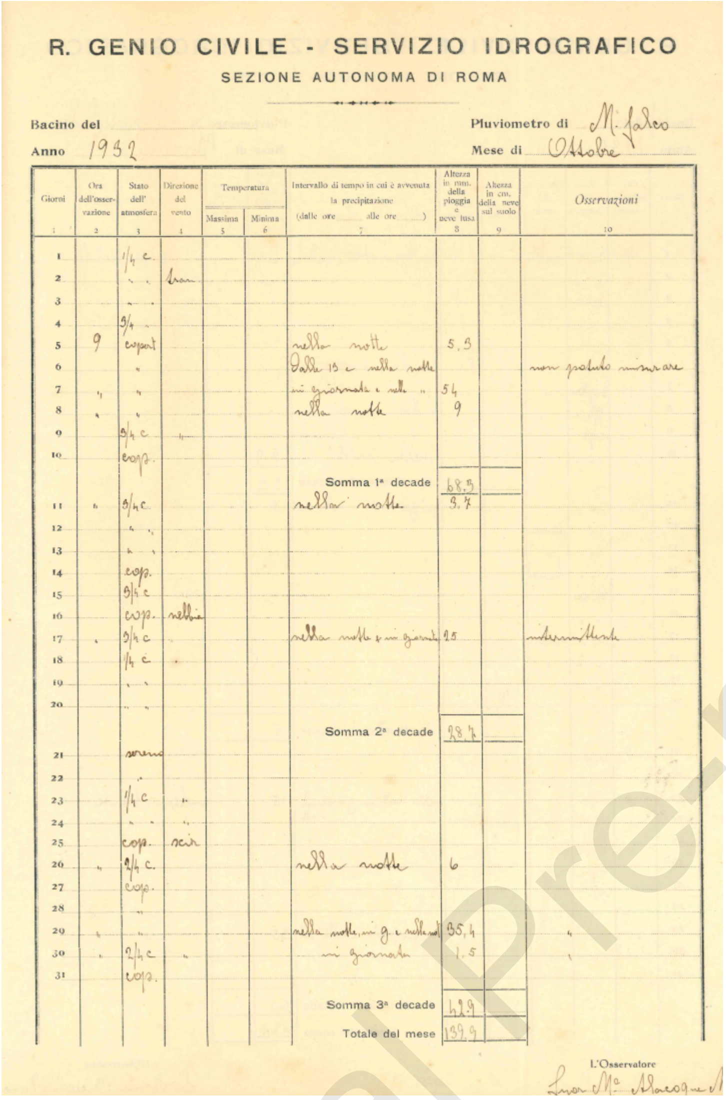


Fig. 2. Rainfall data recorded at the S. Rossore rain gauge (Tuscany-Italy) from October 31, 1966 to November 7, 1966.

(a)


R. GENIO CIVILE - SERVIZIO IDROGRAFICO

SEZIONE AUTONOMA DI ROMA

Bacino del

Pluviometro di M. Falco

Anno 1932

Mese di Ottobre

Giorni	Ora dell'osservazione	Stato dell'atmosfera	Direzione del vento	Temperatura Massima	Temperatura Minima	Intervallo di tempo in cui è avvenuta la precipitazione (dalle ore ... alle ore ...)	Altezza in mm. della pioggia e neve fusa	Altezza in cm. della neve sul suolo	Osservazioni
5	9	coperto				nella notte	5.3		
6		"				dalle 13 e nella notte			non prodotto misurare
7	"	"				in giornata e nella notte	54		
8	"	"				nella notte	9		
						Somma 1ª decade	68.3		
11	"	3/4 c.				nella notte	3.7		
17	"	3/4 c.				nella notte e in giornata	25		intermittente
						Somma 2ª decade	28.7		
26	"	3/4 c.				nella notte	6		
29	"	"				nella notte, in g. e nella notte	35.4		
30	"	2/4 c.				in giornata	1.5		
						Somma 3ª decade	42.9		
						Totale del mese	139.9		

L'Osservatore

Fig. 3. Manual recording of daily rainfall data during the month of October 1932 for Montefalco station (Umbria-central Italy).

2.3 Rainfall time-resolution data collection

Rainfall time resolution data from many geographical areas of the world have been collected by contacting the authors of recent papers in which rainfall data are used. With this objective, a data request was sent to potential participants asking for their cooperation in the development of a database containing information on rainfall time-resolution data at the global scale, by providing for each rain gauge station the complete t_a history, including the geographical coordinates of the installation sites. For each study area, specific details regarding the t_a histories of selected rain gauges can be found in the Results section. In the end, 25,423 rain gauge histories were collected, provided by 32 different research groups, as shown in Fig. 4 and detailed in Table 1.

We note the absence of stations from large and important countries, such as Russia, Germany, France and United Kingdom. This will be the main reason for further developments of the current analysis, which represents, in any case, a necessary and useful first step towards building a global database.

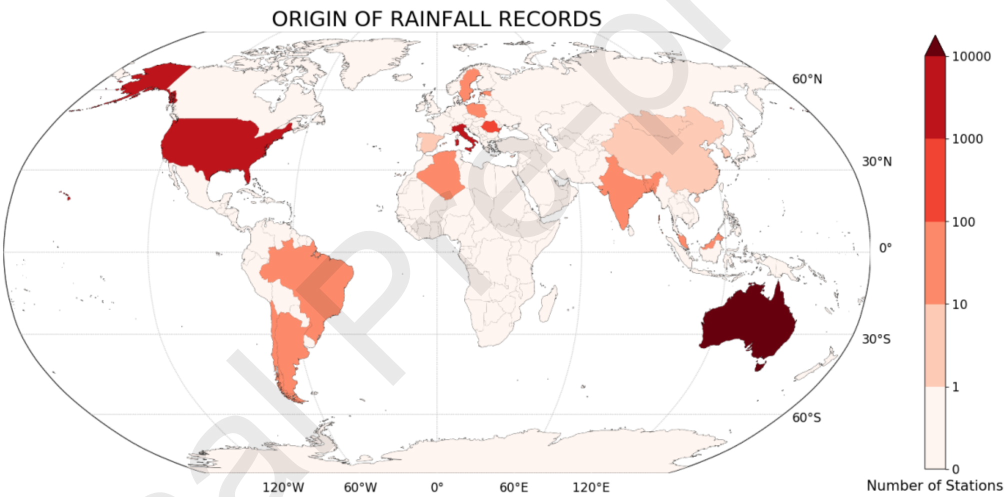


Fig. 4. Geographical position of the rain gauge stations considered in this study.

Table 1. Main characteristics of rainfall recordings for the rain gauge stations included in the database (see also the Supplementary Material – click here).

Country (Area)	Rain gauges [number]	Record length min/max [years]	Beginning of records [year]	Ending of records [year]	Time resolution min/max [minutes]
Algeria (northern region)	30	9/41	1968	2010	1440
Argentina (Prov.Córdoba)	69	2/79	1941	2019	5/1440
Australia (whole country)	17,768	1/180	1805	2019	1/1440
Bangladesh (whole coun.)	35	19/72	1940	2019	180/1440

Brazil (eastern region)	2	35/54	1965	2019	1440
Brazil (northeast region)	18	3	2016	2018	10
Chile (El Rutal)	1	4	2011	2014	5
Chile (central region)	26	23/54	1959	2019	15/60
China (various areas)	7	5/11	2006	2017	10/30
Cyprus (central region)	7	54/139	1881	2019	10/518400
Estonia (whole country)	51	3/133	1860	2019	10/1440
India (Tapi basin)	54	41/92	1930	2019	1/1440
Italy (Benevento)	2	49/135	1884	2019	10/43200
Italy (Calabria region)	119	13/103	1916	2019	1/1440
Italy (Sardinia region)	73	90/98	1921	2019	1/1440
Italy (Sicily region)	18	17/103	1916	2019	5/60
Italy (Tuscany region)	908	1/98	1916	2017	1/1440
Italy (Umbria region)	152	8/98	1915	2019	1/1440
Malaysia (whole country)	46	6/98	1879	2019	1/1440
Malta (whole country)	10	12/76	1922	2019	1/1440
Mongolia (western region)	2	49/57	1963	2019	1/720
Poland (whole country)	53	3/69	1951	2019	60/1440
Poland (Kujaw.-P. region)	10	1/159	1861	2019	5/43200
Poland (Lubelskie region)	11	7/96	1922	2019	5/1440
Romania (whole country)	158	17/135	1885	2019	10/1440
South Korea (Seoul)	1	112	1907	2019	1/480
Spain (Andalusia region)	3	35/77	1942	2019	10/1440
Spain (Barcelona)	1	106	1914	2019	1/1440
Spain (Madrid)	1	100	1920	2019	10/1440
Spain (San Fernando)	1	184	1805	2019	1/>1440
Sweden (Uppsala region)	64	1/126	1893	2019	15/1440
USA (Colorado State)	5732	1/153	1867	2019	1/1440

2.4 Database structure

The database, with detailed information on the rainfall time-resolution data is prepared in *.xlsx format (see also Fig. 5). This file is freely available online in the Supplementary Material (click here) or by asking the corresponding author of this paper.

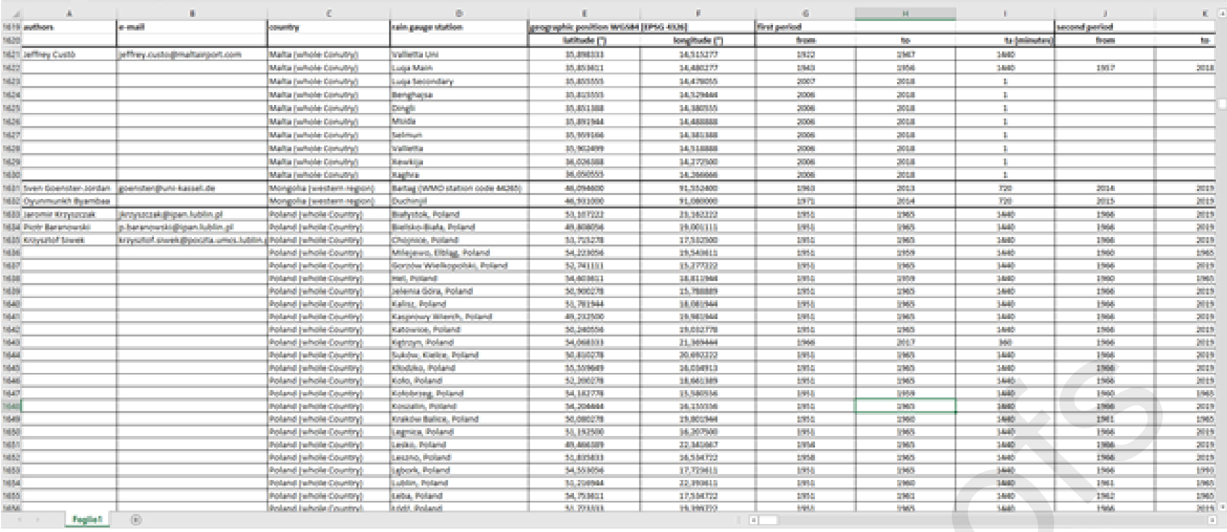


Fig. 5. Screen shot of a small part of the global database with all collected rainfall time resolution data (at this stage the database is composed by 25,425 rows).

3. Results

In this section a review of the main results obtained for the study areas represented in the global database is provided. Note that in the following paragraphs typically the history of all rain gauges for a large region (or whole country) is discussed, while in the Supplementary Material (click here) details for just representative stations can be found.

3.1 Basin of the San Roque Dam (Córdoba Mountains, Argentina)

The Basin of the San Roque Dam (1650 km^2) is located in the geographic center of the South American territory of Argentina, in the Province of Córdoba and collects the waters of the Cosquín and San Antonio rivers, as well as the Las Mojarras and Los Chorrillos streams (Catalini, 2004).

As well as in many other Argentine areas, the first available pluviometric recordings date back to the middle of the last century, and they were recorded on paper by local people, activity that was maintained until the middle of the 1980s. But as in other Latin-American countries, the difficult political and economic situation caused many rain gauges to disappear over the same period.

Initially all the rain gauges, installed by the Provincial Water and Sanitation Direction (DiPAS), were characterized by t_a=1440 minutes. The first rain gauges were installed in 1941, with the building of the new San Roque Dam. The first stations equipped with a digital data-logger (a group of 11 stations managed by the National Institute of Water Center of the Semiarid Region, INA-CIRSA) came into operation in 1985, and nowadays there are 19 stations in the basin. These stations are of ALERT technology type and record every mm of rain, being the records transmitted in real time to a central station and published online (http://sgainacirsa.ddns.net/cirsa/) as part of a warning system. In the last year, the Secretary of Water Resources of the Province installed a further 7 rain gauges that register every 10 minutes, and 2 more ALERT stations as a part of the INA-CIRSA warning system. In 2017 the Secretary of Infrastructure and Water Policy of the Nation installed one more rain gauge station and the first disdrometer in the basin, as a part of the field equipment of the first Argentine Meteorological Radar RMA01 (within the SINARAME project). Moreover, other institutions have installed stations in the basin; nowadays 32 rain gauge stations are operational in the basin, 13 stations more than the original number of 1941 (Fig. 6).

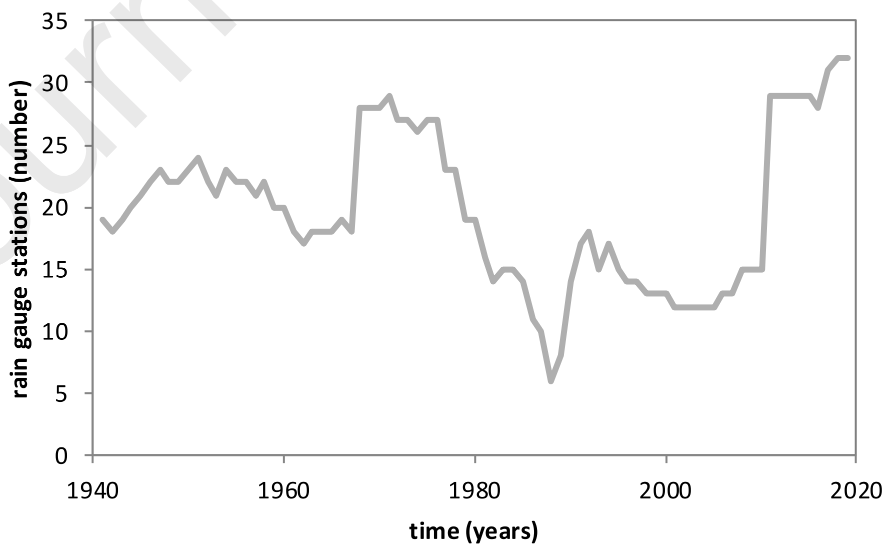


Fig. 6. Rain gauges number evolution with time in the basin of the San Roque Dam (Argentina).

In the case of the San Roque Dam basin, the National Water Institute has operated and maintained since 1985 a telemetric network of 19 rain gauge stations (event measure, used for warning system).

3.2 Australia (whole country)

In Australia, the earliest available rainfall observations in the Bureau of Meteorology's dataset date back to 1826, with monthly data at Tulloona Coolanga station (http://www.bom.gov.au/climate/data/). Observations with t_a of 1440, 180, 30, and 1 minute start from 1832 (Parramatta station), 1920 (Hobart Ellerslie Road station), 1989 (Scone Airport AWS station), and 1994 (Perth Metro station) respectively. Around 18,000 stations have been used over the history of data collection, with almost all stations having data with t_a=1440 minutes. Only 1518, 619, and 580 stations provide data with t_a of 180, 30, and 1 minutes, respectively. The number of active stations for daily observation rose from only a few hundreds to over 8000 from the 1870s to the 1970s, and then declined gradually to around 7000 in the 2000s (Fig. 7). Over recent decades, active daily observation stations have further declined to 4765 in 2019, while the number of stations at sub-daily temporal-resolution has been increased to 759 (for t_a=180 minutes) and 556 (for t_a=1 and 30 minutes) (Fig. 7). Data at coarser temporal resolutions are available for longer periods, as such the maximum record length with t_a of 1440, 180, 30, and 1 minute are 161, 99.5, 30.3, and 25.5 years respectively. Spatially, the eastern and western seaboard of Australia accommodate the highest number of stations, followed by the northern territory and south-coastal region, whereas the vast region of inland Australia (mostly arid) accommodates a relatively fewer number of stations, with some parts of this region without stations (Fig. 8).

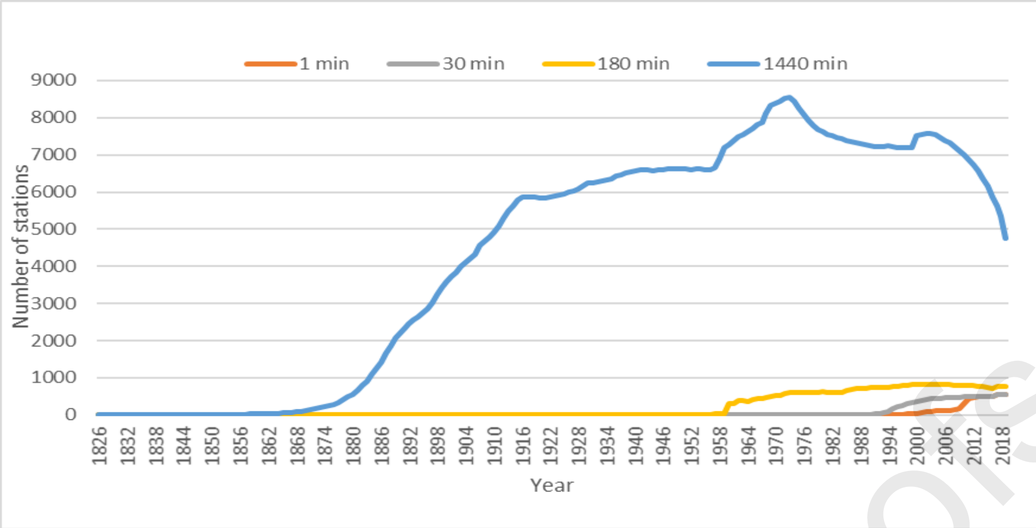


Fig. 7. Rain gauges number evolution with time in Australia.

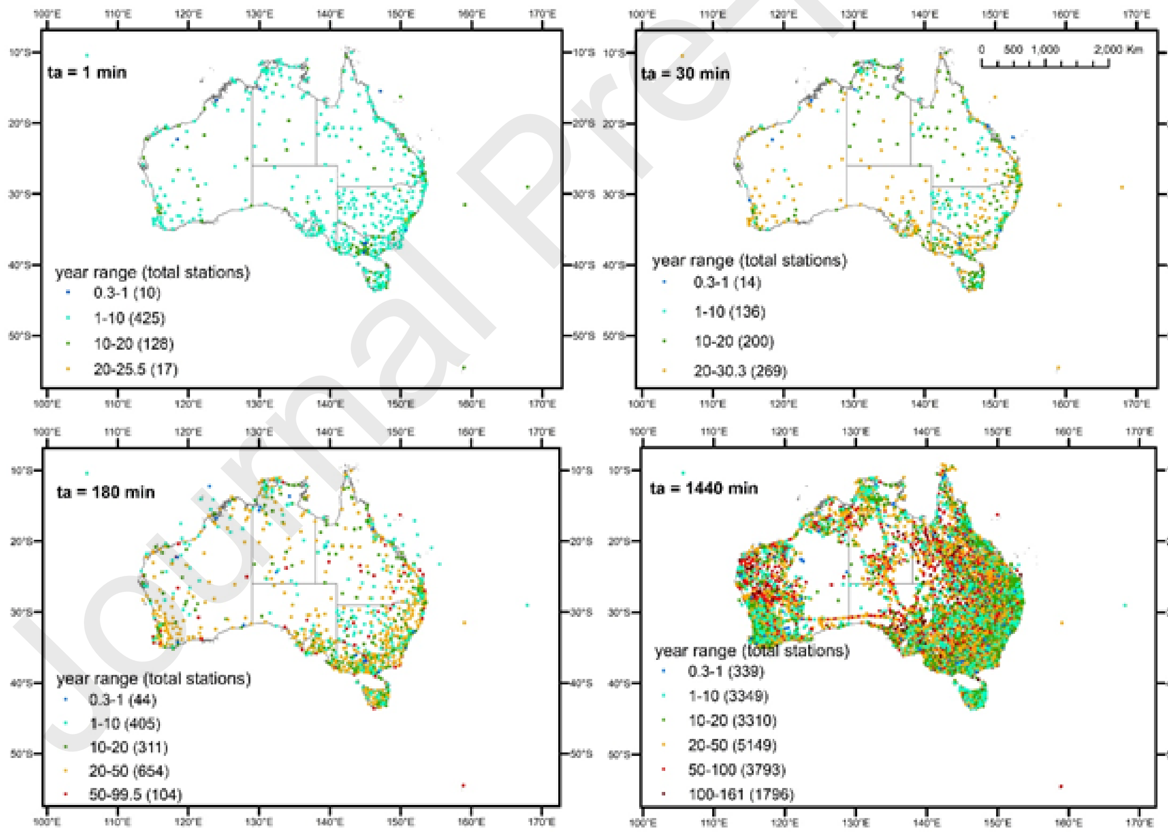


Fig. 8. Spatial distribution of rain gauges with temporal aggregation period, t_a, of 1, 30, 180, and 1440 minutes. Colors indicate available record length in years, while stations with record length below one year for 1, 30, and 180 minutes and below ten years for 1440 minutes are not shown. Total number of stations that have a respective range of record length is shown within parenthesis in legend.

3.3 Bangladesh (whole country)

Rainfall estimation in Bangladesh started in 1948, when the country was known as East Pakistan. Initially, the Pakistan Meteorological Department (PMD) installed 9 rainfall stations with t_a=1440 minutes, immediately followed by 8 more stations with the same t_a. After the independence of Bangladesh in 1971, between 1973 and 2000 the Bangladesh Meteorological Department (BMD) established 12 more stations with t_a=1440 minutes (Fig. 9). During the liberation war in 1971, rainfall data are missing from almost all station records across the country. From 2003, 35 rainfall stations characterized by t_a=180 minutes were installed. The maximum record length of data series with t_a equal to 1440 and 180 minutes are 72 and 17 years, respectively. Spatially, the south-western regions have the highest number of stations, followed by the hilly region in the south-eastern and north-eastern regions, with only a few stations in the north-western arid region.

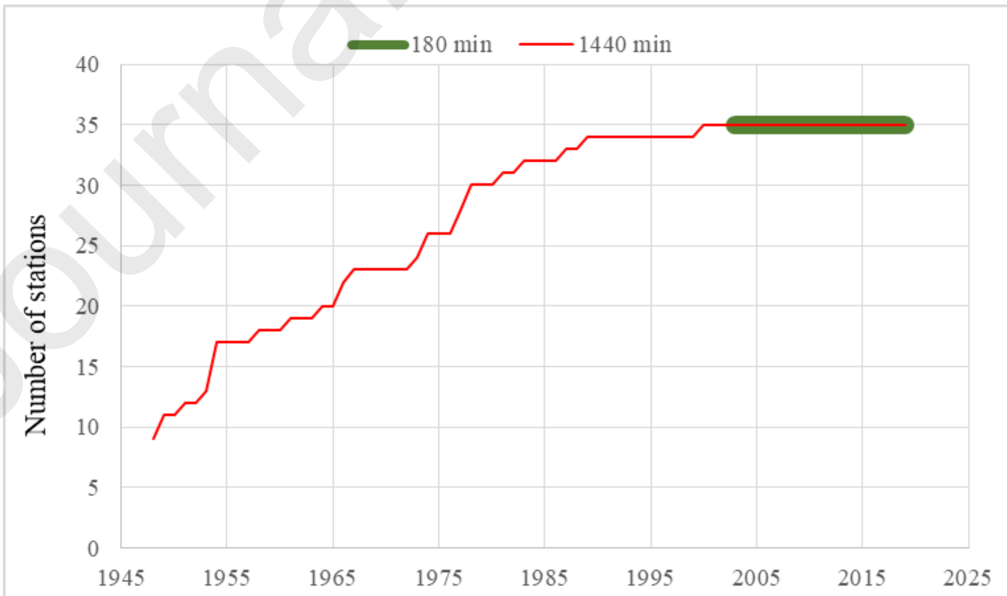


Fig. 9. Rain gauges number evolution with time in Bangladesh, including the adopted t_a.

3.4 Brazil (north-east region)

In the north-east semiarid region of Brazil, stations were set up by the National Center for Monitoring and Early Warning of Natural Disasters. The network includes 595 stations in total; 95 units contain additional measurements of air temperature, relative humidity, solar radiation, wind speed and soil temperature. This set of stations is composed of a rain gauge (model PluvDB, DualBase, Santa Catarina, Brazil) and volumetric water content sensors (model EC-5, Decagon Devices, Pullman, WA, USA) installed at 10 and 20 cm. Data from this network are used in the monitoring of drought risk over the region. Example applications include calculating monthly averages of soil moisture and real-time monitoring of relative extractable water (Zeri et al. 2018). The temporal aggregation of rainfall data is 10 minutes.

3.5 Estonia (whole country)

Precipitation measurements in Estonia began in 1860 using a Nipher rain gauge, while the first Tretivakov rain gauge was installed in 1950 (see also Fig. 10). Automatic rainfall measurements started in 2009, through the use of weighing devices, initially of Vaisalas VRG-101 type and later of OTT Pluvio2 type.

Therefore, temporal aggregation of rainfall data observed in Estonia varies, depending on the specific period and type of station. During the Soviet era, there were two types of stations, denoted primary and secondary. From 1860 to 1940, there was one measurement per day in all stations. During the Second World War, from 1941 to 1944, a different observation time was used: in primary stations at 5:00 am, 11:00 am and 7:00 pm; in secondary stations at 5:00 am and 7:00 pm. Successively, in the primary stations the temporal aggregation was 360 and 720 minutes, depending on the period, while in the secondary stations it was 720 minutes. Finally, starting from 2009, a widespread automatization of rain gauge stations allowed temporal aggregations of up to 10 minutes.

From a quantitative point of view, at the end of the 19th Century only 5 rain gauge stations were installed. They totaled 150 in 1930, decreased during the Second World War and declined to 51 by 2018.

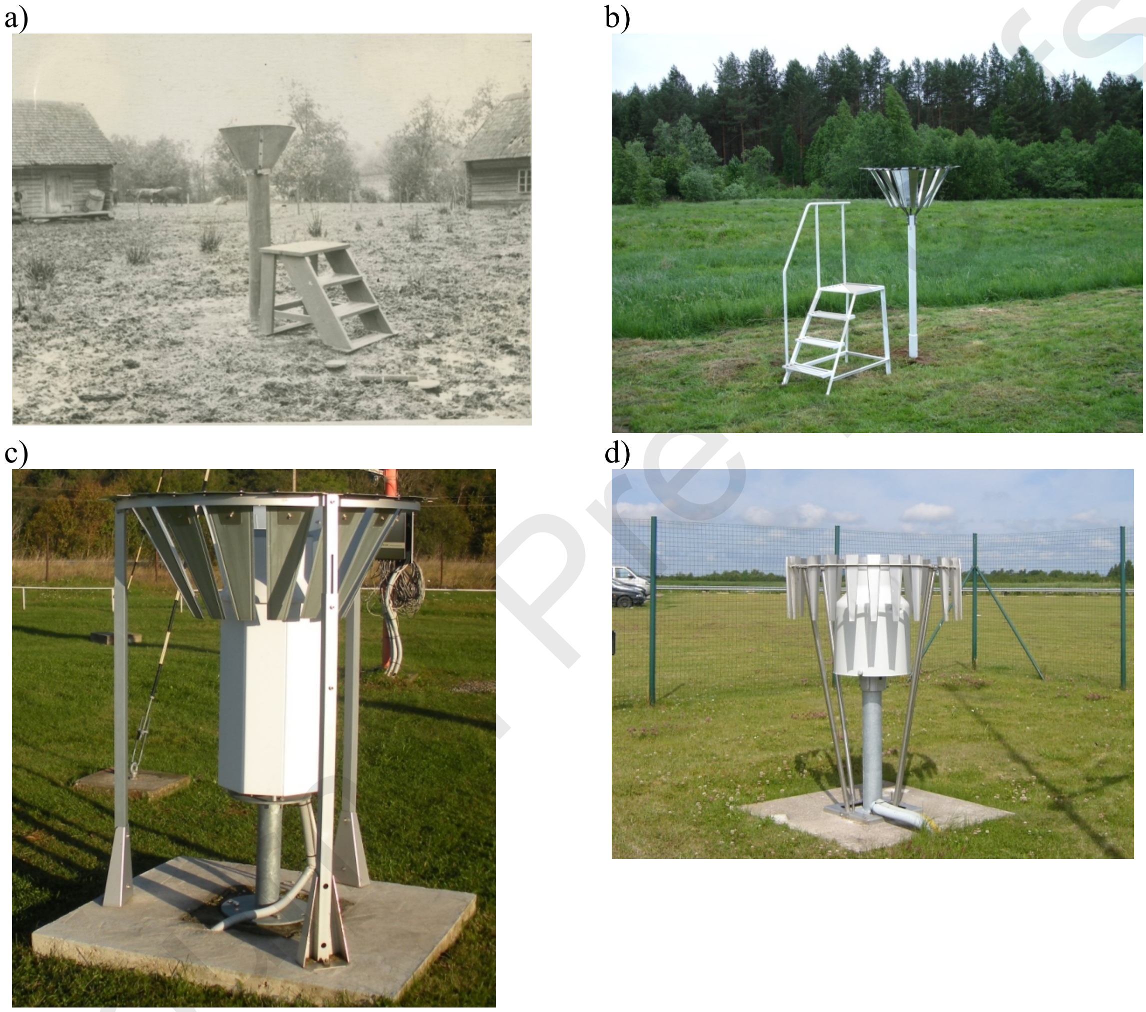


Fig. 10. Different rain gauge stations adopted in Estonia through the years: a) gauge with Nipher wind shield; b) gauge with Tretyjakov wind shield; c) gauge VRG101 by Vaisala; d) gauge Pluvio2 by OTT.

3.6 Tapi basin (central India)

The Tapi basin is situated in the northern part of the Deccan plateau of central India and extends to 65,145 km^2. India has some of the oldest meteorological observations in the world. The first observatory was established in Calcutta (now Kolkata) in 1785 and Madras (now

Chennai) in 1796. In the first half of the 19th century, several observatories began functioning in India with data characterized by t_a=1440 minutes. Initially (from the year 1925) in the Tapi Basin the rain gauges installed by the India Meteorological Department (IMD) were characterized by t_a=1440 minutes. From the year 1969, the IMD installed rain gauges with t_a=60 minutes. The first station equipped with a digital data logger (t_a=1 minute) managed by the National Institute of Wind Energy (NIWE) was installed in 2012. Currently in the Tapi basin only 4 rain gauge stations are characterized by t_a=1minute.

3.7 Campania region and Benevento city (southern Italy)

The Campania region (a coastal area of southern Italy extending to 13,671 km^2) is among the Italian regions with the longest pluviometric series. The first available pluviometric recordings date back to 1727 in Naples under the guidance of Nicola Cyrillus – member correspondent of the London Royal Society – but they stopped in 1754. Successively, we remember the meteorological series of the Regia Specula of Capodimonte, whose first rain observations date back to 1821 thanks to Carlo Brioschi, which are reported until 1950. Among the pluviometric series that have been interrupted over time, we mention also that of the Vesuvian Observatory, which started in 1864 and ended in 1971.

However, several other instrumental meteorological series are also present in the Campania region, which continue to today. These include the Geophysical Observatory of the Federician University from 1865, the Meteorological Observatory of the Sanctuary of Montevergine from 1884, and the Meteorological Observatory of Benevento from 1869 to 1999. However, the counting of ancient correspondences shows that in other parts of inland Campania rather sporadic rainfall observations were held between the end of the 18th century and the beginning of the 19th, but they did not last until the present day.

Figure 11 shows the temporal evolution of the rain gauge network in the Campania region, showing the cumulative number of rain gauges from 1727 to 2019, with an interruption between the end of 18th century and the beginning of 19th. Afterward, a strong and sudden increase occurred around 1920, when the rain gauge network scaled from tens to hundreds of units. After this date, the network oscillates around 200 rain gauges, with a weak decrease in recent times.

In the Supplementary Material (click here) of this paper, as well as in Table 1, detailed information regarding the t_a history in the Campania Region referring only to very old stations located at Benevento are reported.

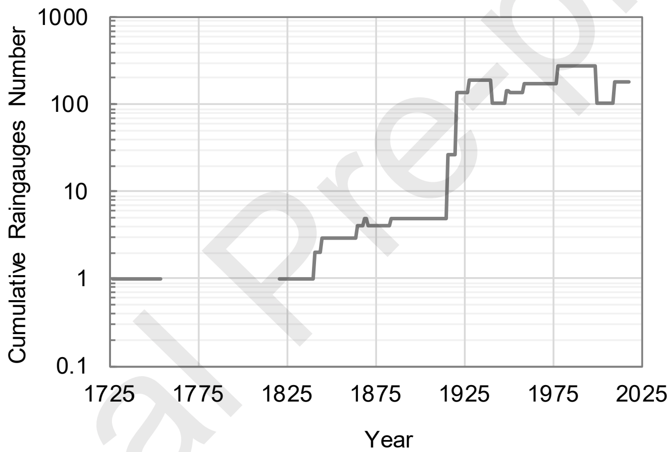


Fig. 11. Rain gauges cumulative number evolution with time in Campania region, southern Italy. The vertical axis is in log-scale.

3.8 Calabria region (southern Italy)

The Calabria region covers a surface of 15,080 km^2 and belongs to the southernmost part of the Italian peninsula. In this region, rainfall data collection started in the second decade of the past century. The first rain gauges were installed by the Italian National Hydrographic Service (INHS) and were characterized by a temporal aggregation of 1440 minutes. From 1916 onward, the rain gauge network improved both in terms of station numbers and in terms of technology. It went from manual stations first to registration with paper roll stations, then to registration on digital data-loggers. In particular, the number of rain gauges increased from 1916 to 1940 when the Calabria territory had a coverage of 229 stations; it decreased after 1940 with the beginning of the Second World War due to obvious problems in data collection. After this period the number of rain gauges increased again, reaching a maximum of 223 stations in 1967. After this date, the rain gauge network was progressively reduced until today, with some reductions at the end of the 20th Century when the Multi-Risk Functional Centre of the Regional Agency for Environmental Protection of Calabria replaced the INHS in the management of the network. This updated the technology of the rain gauges and now all the stations automatically send real-time data to a telemetry network. The rain gauge number evolution with time is shown in Fig. 12.

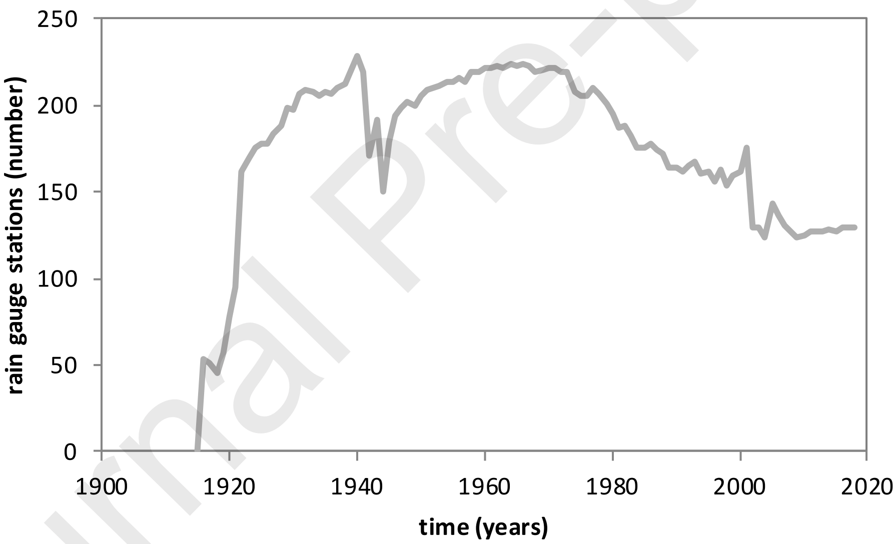


Fig. 12. Rain gauges number evolution with time in Calabria, southern Italy.

As regards the temporal aggregation of the data, in spite of the technological evolution of the stations, from 1916 to 1989 the rain gauge network has been characterized by t_a=1440 minutes and only after 1989 have rainfall data been collected with t_a of 5, 20 or 30 minutes. In fact, before 1989 in several rain gauges data were recorded on paper rolls, which recently have been digitized, but data have not been extracted. Currently all the rain gauges of the

Calabria region are characterized by t_a=1 minute. Figure 13 shows the percentage of rain gauge stations in Calabria with specific temporal aggregation.

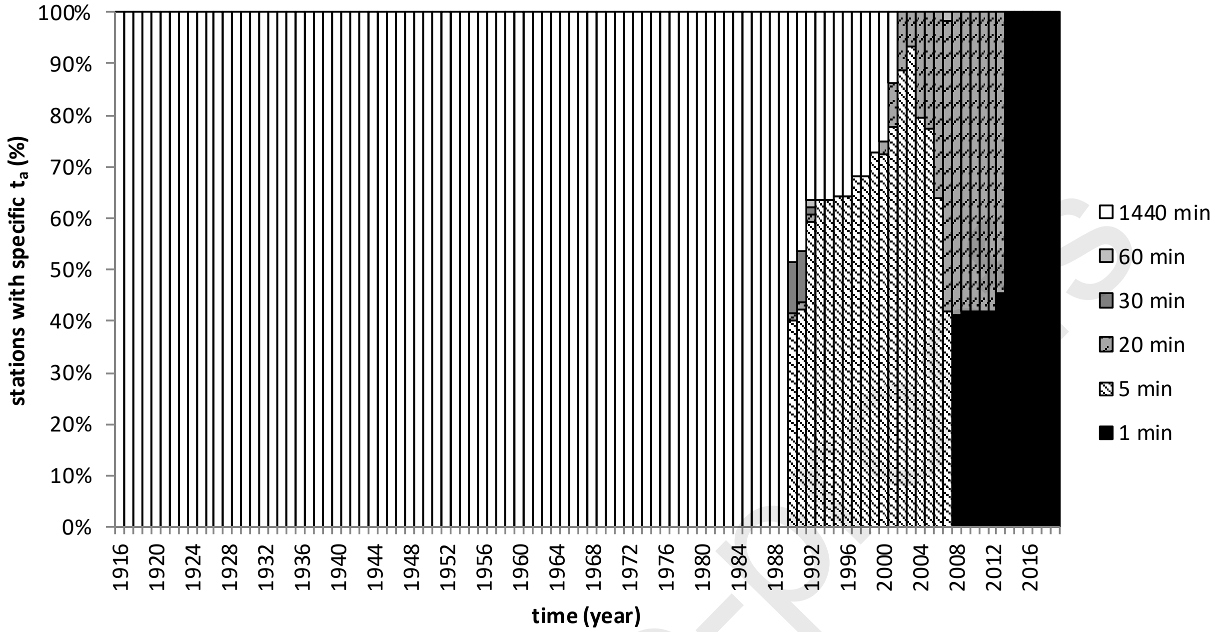


Fig. 13. Percentage of rain gauge stations in Calabria (southern Italy) with specific temporal aggregation, t_a.

3.9 Sicily region (southern Italy)

The Sicilian Water Observatory, formerly the Regional Hydrographic Office, is in charge of the hydro-meteorological monitoring of Sicily region since 1917. Since the beginning of the '20s the monitoring network consisted of almost 200 mechanical stations, including self-recording gauges (~70%) and non-recording rain gauges (~30%), the latter providing only total rainfall occurring at daily or longer time-scales. The number of gauges has rapidly increased, reaching a maximum of 336 rain gauges in 1993.

Since 1940 the non-recording rain gauges have been gradually abandoned and/or replaced by self-recording mechanical gauges, mostly of tipping bucket type (SIAP UM8100 or UM8170). Although in principle self-recording gauges can provide hourly data, only annual maxima rainfall data at sub-daily durations have been made available by the Water Observatory. In particular, annual maxima for durations of 1, 2, 3, 4 or 5 days were made available since 1916 for more than 250 rain gauges. The first annual maximum rainfall data at 1, 3, 6, 12 and 24 hours for 27 rain gauges were published in 1928. Annual maxima for durations lower than 1 h were occasionally published for a small selection of the rain gauges since 1951.

Rainfall data aggregated for each station at daily, monthly and annual time-scales have been published in yearly bulletins since 1916. The yearly bulletins, available on the Water Observatory website from 1924 to 2015 (http://www.osservatorioacque.it/), essentially collect the data observed by mechanical stations.

In 2002 a new monitoring network consisting of automatic hydro-meteorological gauges has been realized by the Water Observatory in order to improve the spatial coverage of the traditional network, as well as to make the observed data available in real-time, for instance, for the purposes of civil protection against hydro-meteorological hazards. At the end of 2016, the real-time monitoring network was equipped with 251 stations, including 213 rain gauges (MICROS or NESA with 1000 cm^2 funnel area). These rain gauges, together with 87 rain gauges operated by the Regional Agrometeorological Information Service (SIAS) and 7 rain gauges operated by the Regional Department of Civil Protection, regularly provide data to the national monitoring network operated by the National Department of Civil Protection. The Water Observatory also manages another small network of 43 rain gauges recently installed to fulfill planning purposes related to water quality conservation.

Figure 14 illustrates both the non-automatic (in grey) and automatic (in black) rain gauge networks consistency from 1916 to 2015.

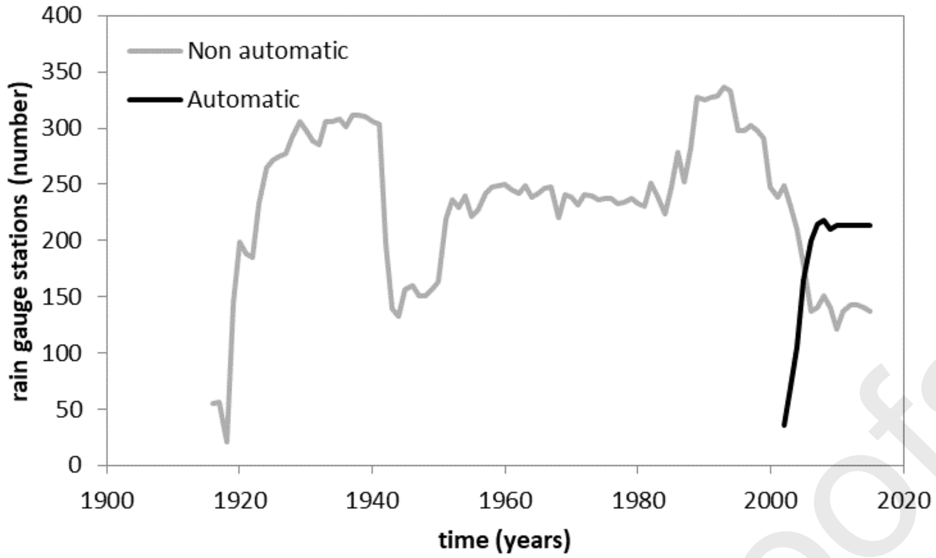


Fig. 14. Consistency of the non-automatic and automatic rain gauge networks operated by the Water Observatory

With reference to the temporal aggregation of rainfall data, the automatic stations operated by the Water Observatory report pre-alarm or alarm conditions by increasing the measurement time interval (usually equal to 30 minutes) to 15 and 5 minutes respectively when rainfall occurs. Figure 15 shows the variation of temporal aggregation of rainfall data provided by the Water Observatory.

From the end of 2018, several mechanical rain gauges have fallen into disuse due to economic reasons, so that the real-time monitoring network is basically the only one currently in operation. Therefore, the yearly bulletins from 2019 onward will mainly contain data from the automatic stations, once that the quality of the data will be verified through appropriate validation techniques.

In view of this relevant change in rainfall monitoring, in order to preserve the continuity in rainfall recording, most of the automatic stations have been installed close to the mechanical stations, so that the new records can be attributed to the same sites. Conventionally, an automatic station and a mechanical station are considered as the same site if their distance is below or equal to 100 m, with a few exceptions.

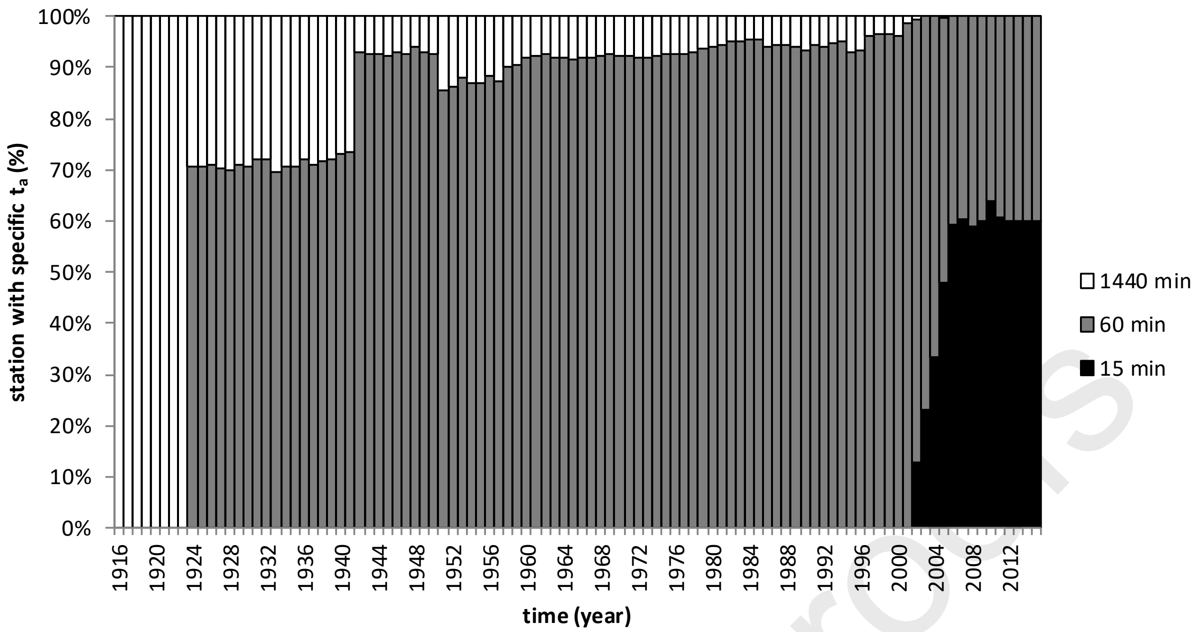


Fig. 15. Temporal aggregation of rainfall data of the network operated by Water Observatory of Sicily, southern Italy.

3.10 Tuscany region (central Italy)

Tuscany is a region of central Italy with an extent of about 23,000 km^2. The INHS managed the first available pluviometric records in Tuscany, as well as in other inland and peninsular Italian areas, starting from the second decade of the last century. The Regional Hydrological Service of Tuscany (SIR) have managed INHS's rain gauges and historical pluviometric records since the 2000s. Data from other monitoring networks, like the Agency for development and innovation in the agricultural forestry sector of Tuscany (ARSIA-Tuscany) and the Agency for environmental protection of Tuscany (ARPAT), recorded by automatic stations with t_a=1 minute, are also managed by SIR. Figure 16 shows the evolution of rain gauge numbers over time, from which it can be seen that 59 rain gauges (e.g. Pontassieve, Montevarchi, Livorno and Grosseto) were installed in 1916.

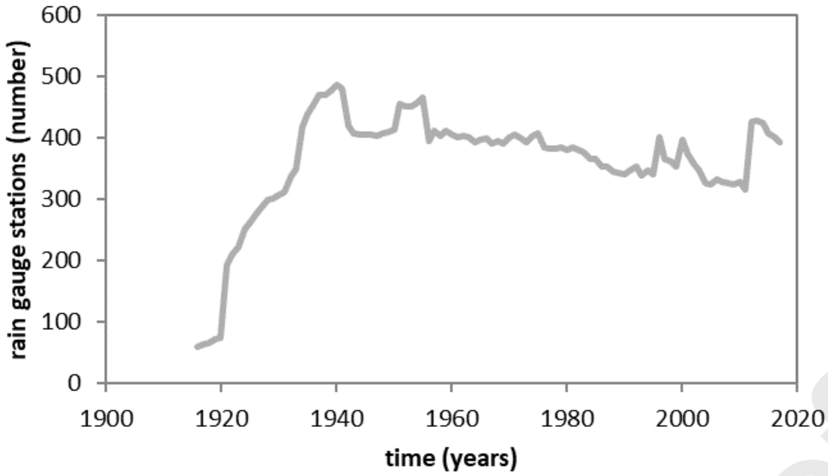


Fig. 16. Rain gauges number evolution with time in Tuscany, central Italy.

As shown in Fig. 17, all rain gauge stations were initially characterized by t_a=1440 minutes. The first rain gauges with registration on paper rolls were installed since 1923, and successively they remained a small percentage with respect to the total number. The first stations equipped with a digital data-logger became operative in 1990. Currently in Tuscany there are 356 rain gauges characterized by t_a=1 minute, 34 stations characterized by t_a=5 minutes, 2 by t_a=60 minutes and only one for which the data recording takes place every 1440 minutes.

Table 2 shows an interesting detail of t_a history for some representative stations of Tuscany. Rain gauges can be divided into the following main groups: 1) stations belonging to the monitoring network of the Arno River basin; 2) stations belonging to the monitoring network of the Serchio River basin; 3) stations belonging to the monitoring network of the Ombrone Grossetano River basin; 4) stations belonging to the monitoring network of the Magra River basin; 5) stations belonging to the traditional monitoring network; 6) stations belonging to the ARSIA monitoring network.

Fig. 17. Percentage of rain gauge stations in Tuscany (central Italy) with specific temporal aggregation, t_a.

Table 2. Different groups of representative rain gauge stations of Tuscany (central Italy) with time evolution of the adopted temporal aggregation, t_a.

Rain gauge station	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]
Monitoring network of the “Arno” river basin					
Capannoli	*1994/1996* **1440**	*1996/2017* **1**			
Incisa Valle	*2000/2001* **1440**	*2001/2017* **5**			
Lamole	*1996/2012* **5**	*2012/2017* **1**			
Poggio Aglione	*1994/1999* **1440**	*1999/2001* **60**	*2001/2017* **1**		
Monitoring network of the “Serchio” river basin					
Monte Macina	*1996//2013* **1**				
Pedona	*1999/2001* **1440**	*2001/2013* **1**			
S.Pellegrino in Alpe	*1921/1955* **1440**	*1955/1977* **60**	*1977/1996* **5**	*1996/2013* **1**	
Vallelunga	*1999/2001* **1440**	*2001/2017* **1**			
Monitoring network of the “Ombrone Grossetano” river basin					
Casteani	*2002/2010* **60**	*2010/2017* **1**			
Monticchiello	*1937/2003* **1440**	*2003/2010* **1**			
Monticiano la pineta	*1921/2014* **1440**	*2014/2017* **1**			
Vagliagli	*1977/2017* **5**				
Monitoring network of the Magra river basin					
Equi Terme	*1937/1957* **1440**	*1957/2011* **60**	*2011/2017* **1**		
Minucciano	*1942/1957* **1440**	*1957/1999* **60**	*1999/2017* **1**		

Parana	*1935/1958*	*1958/2011*	*2011/2017*	
	1440	**60**	**1**	
Rocca Sigillina	*1941/1958*	*1958/2011*	*2011/2017*	
	1440	**60**	**1**	
Traditional monitoring network				
Arezzo	*1916/1928*	*1928/1929*	*1929/1992*	*1992/2017*
	1440	**60**	**5**	**1**
Consuma	*1923/1940*	*1940/1990*	*1990/1992*	*1992/2017*
	1440	**60**	**5**	**1**
Pontedera	*1916/1982*	*1982/1985*	*1985/1996*	*1996/2017*
	1440	**60**	**5**	**1**
Viareggio	*1921/1945*	*1945/1951*	*1951/1996*	*1996/2017*
	1440	**60**	**5**	**1**

3.11 Umbria region (central Italy)

In the Umbria region (an inland area of central Italy extended 8456 km^2), as shown in the rain gauge numbers evolution with time (Fig. 18), the first available pluviometric recordings date back to the second decade of the 20^{th} Century.

Fig. 18. Rain gauges number evolution with time in Umbria region, central Italy.

As it can be seen in Figure 19, initially all the Umbrian rain gauge stations (installed by the INHS) were characterized by t_a=1440 minutes. The first rain gauges with registration on paper rolls were installed in 1927, and successively they have always been a small percentage of the total number. The first stations equipped with a digital data-logger (a group of 37 stations managed by the National Research Council) came into operation in 1986, while the transition to digital of the INHS' stations, in the meantime became properties of the Regional

Hydrographic Service (RHS), began in 1990 and was completed in 2011. Currently all the rain gauge stations of the Umbria region are characterized by t_a=1 minute, except for 9 stations for which a data transmission takes place every 5 minutes.

Table 3 shows a detail of the t_a history for some representative stations of the Umbria region. It can be seen that all rain gauges are divided into the following main groups: 1) very old stations installed by the INHS that over the years have adopted all types of recording (initially manual with t_a=1440 minutes, successively over paper rolls with t_a=30 minutes, finally digital with t_a=1 or 5 minutes); 2) stations installed by the INHS after the Second World War that have typically adopted only two different types of recording (initially manual, then digital); 3) stations installed by the RHS within the last three decades, all with t_a=1 minute; 4) stations installed by the National Research Council since 1986, all with t_a=1 minute.

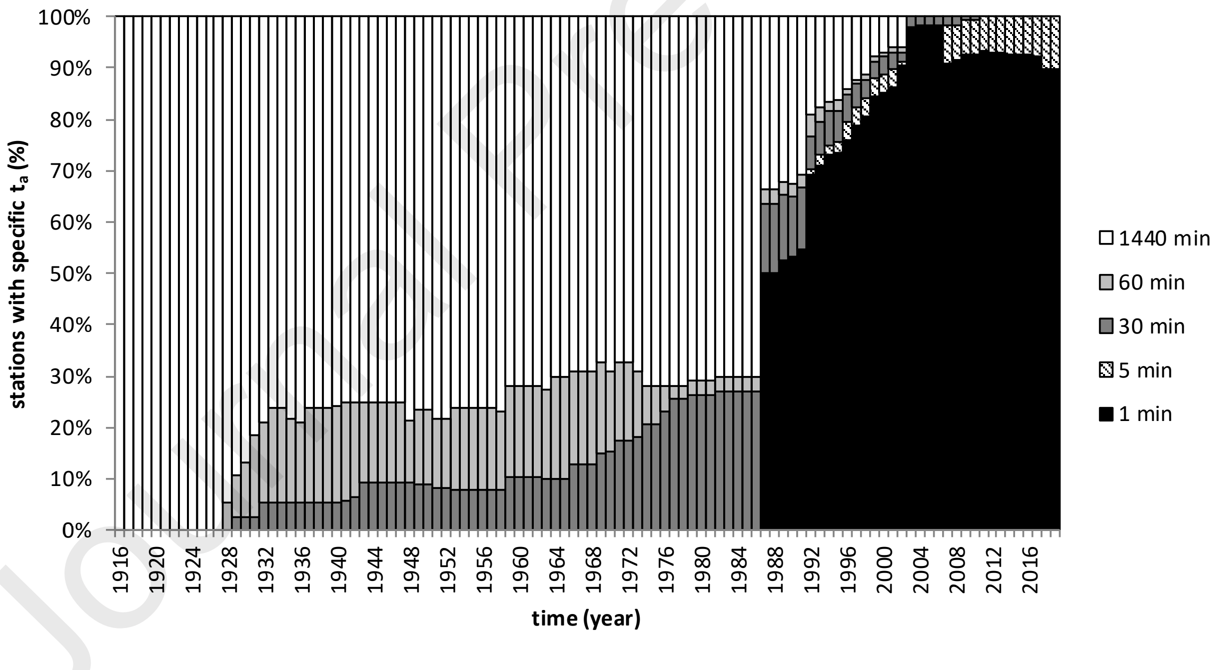


Fig. 19. Percentage of rain gauge stations in Umbria region (central Italy) with specific temporal aggregation, t_a.

Table 3. Different groups of representative rain gauge stations of the Umbria region (central Italy) with the time evolution of the adopted temporal aggregation, t_a.

Rain gauge station	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]
very old stations installed by the Italian National Hydrographic Service					
Cannara	*1915/1940*	*1992/2019*			
	1440	**1**			
Foligno	*1915/1927*	*1928/1934*	*1938/1952*	*1953/1973*	*1993/2019*
	1440	**60**	**1440**	**60**	**1**
Perugia	*1915/1931*	*1932/1996*	*2008/2010*		
	1440	**30**	**1**		
Todi	*1921/1930*	*1931/1942*	*1948/1958*	*1959/1991*	*1992/2019*
	1440	**60**	**1440**	**30**	**1**
stations installed by the Italian National Hydrographic Service after the Second World War					
Abeto	*1951/1998*	*2007/2019*			
	1440	**1**			
Calvi dell'Umbria	*1951/2002*	*2007/2019*			
	1440	**5**			
Lago di Corbara	*1963/1992*	*1993/2019*			
	1440	**1**			
Sellano	*1951/2000*	*2007/2019*			
	1440	**5**			
stations installed by the Regional Hydrographic Service					
Casa Castalda	*1992/2019*				
	1				
La Bruna	*2011/2019*				
	1				
Monte Cucco	*1996/2019*				
	1				
Ponte Felcino	*1992/2019*				
	1				
stations installed by the National Research Council					
Cantinone	*1986/2018*				
	1				
Fosso Impiccati	*2000/2018*				
	1				
Monte Bibbico	*1986/2018*				
	1				
Valfabbrica	*1986/2018*				
	1				

3.12 Malaysia (whole country)

The rainfall stations in Malaysia started to be installed in 1878 at Tanglin Clinic Kuala Lumpur (formerly known as Tanglin Hospital). The early rain gauge stations were non-recording rain gauge type and were unable to produce rainfall intensity for any duration less than 24 hours. Later on, mechanical rainfall instruments were installed to record the data on cylindrical drums. Although the rain gauges were not automatic or data-logging the charts were digitized and the rainfall data for shorter durations were extracted.

In 2019, 463 stations are included in the rainfall network of the Department of Irrigation and Drainage. Furthermore, other agencies such as Malaysian Meteorological Department, Tenaga National Berhad (the company that generates and distributes electricity in the West Malaysia) and Plantation companies also collect rainfall data in the country.

3.13 Mongolia (western region)

The two meteorological stations Baitag (46.095°N, 91.552°E, 1186 m a.s.l., WMO station code 44265) and Duchinjil (46.931°N, 91.080°E, 1951 m a.s.l.) were installed in Western Mongolia in 1963 and 1971, respectively. Initially, Duchinjil was classified by the National Agency for Meteorology and Environmental Monitoring of Mongolia (NAMHEM) as a meteorological post but since 1976 as an official meteorological station. At both stations, a Tretyakov manual precipitation gauge was set-up. Vaisala AWS310 automatic climate stations were installed in addition to the mechanical instruments at the Baitag and Duchinjil sites in 2014 and 2015, respectively, including an unheated Vaisala rain gauge RG13 with a pulse-based tipping-bucket mechanism. The RG13 is covered with a plastic bag from October to May, so that in cases of snowfall only the manual Tretyakov instrument is used for measurements.

At both stations, the precipitation amounts collected by the Tretyakov gauges are manually measured by the station operator every 12 h (t_a=720 minutes; 8 a.m. and 8 p.m.). In case of continuing precipitation, the measurement is only made after the event is finished. The RG13 logs data with a temporal resolution of one minute (t_a=1 minute). Every 12 h, precipitation data collected by the manual as well as the automatic measuring instruments are sent to the NAMHEM in Ulaanbaatar. Additionally, the Baitag and Duchinjil station operators summarize the one-minute precipitation data of a month to a temporal aggregation period of

10 days and a month. The one-minute as well as the aggregated data are then quality checked by a local NAMHEM engineer and transferred to the NAMHEM in Ulaanbaatar.

3.14 Kujawsko-Pomorskie region (Poland)

Precipitation stations considered in this study are situated in the Kujawsko-Pomorskie (Kuyavian-Pomeranian) region in north-central Poland. The stations are operated by the Institute of Technology and Life Sciences, ITP (functioning as the Institute for Land Reclamation and Grassland Farming, IMUZ until 2009). One of the stations is situated in the city area (Bydgoszcz) and the others are located in the rural areas.

Within the whole period of measurements (since 1861 until now) standard rain gauges operated manually have been used to collect rainfall. In the period 1966-1993, a pluviograph with paper strips was used additionally at Bydgoszcz station and since 1998 rain gauges with automatic registration of data have been used at all stations.

The station with the longest data series and representative for regional climate characteristic is situated in Bydgoszcz. Precipitation measurements started in 1861 and continued until now. In the years 1906–2005 the meteorological station was located in the experimental area of the agricultural institutes in Bydgoszcz in an open space of the city center (φ=53°07' N, λ=18°01' E). Since the middle of 2005, the station has been situated about 3 km from the previous point in the experimental plot of the ITP (φ=53°06' N, λ=18°01' E). For the years 1861-1889 monthly (t_a=43200 minutes) precipitation totals were available. The daily (t_a=1440 minutes) precipitation dataset covers the period from 1890 onwards. There are some incomplete short series of daily data in the Second World War time. Since April 1945 full documentation with some events as storm, heavy rainfalls have been recorded.

In the years 1966-1993, in the frost-free period, from April to October, precipitation sums with 5 minutes step (t_a=5 minutes) were recorded using pluviographs with paper strips changed manually every day at 6 a.m. UTC. The time-resolution of pluviograph strips is 10 minutes. The 5-min precipitation totals were determined as the middle values between the lines separating two adjacent 10-min periods. The pluviograph strip charts with 5-min time-step were digitized. In 1997, due to the installation of an automatic device, the data resolution changed to 1 h (t_a=60 minutes) and it is so until now.

The ITP also operates several stations situated in rural areas. Two of them (located in the Noteć river catchment) have over 45 year of recorded data series. Więcławice (φ=52°51' N, λ=18°19' E) represents arable land with history of precipitation as from 1954 onwards. In the period 1954-1981 the data are available with t_a=1440 minutes and from May 2003 onwards with t_a=60 minutes resolution. In the other years only with monthly step. Frydrychowo (φ=53°00' N, λ=17°56 E) installed in a grassland and provides data from 1972 till 1997 (t_a=1440 minutes) and from June 1997 onwards (t_a=60 minutes).

Long rainfall daily (t_a=1440 minutes) data series are available from three stations for which meteorological measurements have already been terminated. Two of these stations were located in grasslands, one in the Noteć river catchment (Prądki, φ=53°03' N, λ=17°57' E) from April 1975 till 1994 and the second in the Lower Wisła (Vistula) river catchment (Grabowo, φ=53°16 N, λ=18°16 E) from 1971 till 1994. The third station was located in arable land (Polanowice/Rusinowo, φ=52°40 N, λ=18°19 E) with daily rainfall records from 1979 to 1993 at Polanowice, from 1993 to 1997 at Rusinowo, a nearby location.

Since April 2008, two new automatic stations have been operated by ITP. One of them is situated in the north edge of Bydgoszcz (Myślęcinek, φ=53°10' N, λ=18°2' E) and has been registering the rainfall data with resolution t_a=30 minutes. The second one is located in the arable land (Samszyce, φ=52°60' N, λ=18°69' E) with 1-h (t_a=60 minutes) records. Since November 2018 precipitation data from two stations (grasslands in the Noteć river catchment at Smolniki; arable land in the watershed between Odra and Wisła at Kolonia Bodzanowska) are available at high resolution (t_a=10 minutes).

Figures 20 and 21 show the evolution of rain gauge stations number operated by the ITP and percentage of stations with specific temporal aggregation, respectively.

In the last years the number of rainfall measurement stations installed in Kujawsko-Pomorskie region by different institutions has been expanded. The resolution has been evolving toward a resolution of t_a=10 minutes or even less.

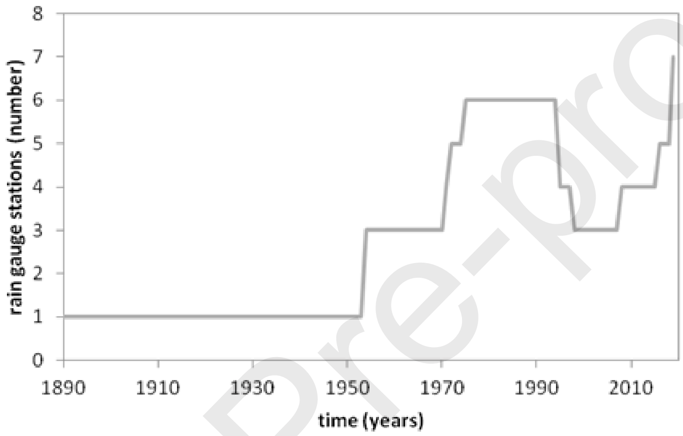


Fig. 20. Rain gauges (operated by the ITP) number evolution with time in the Kujawsko-Pomorskie region.

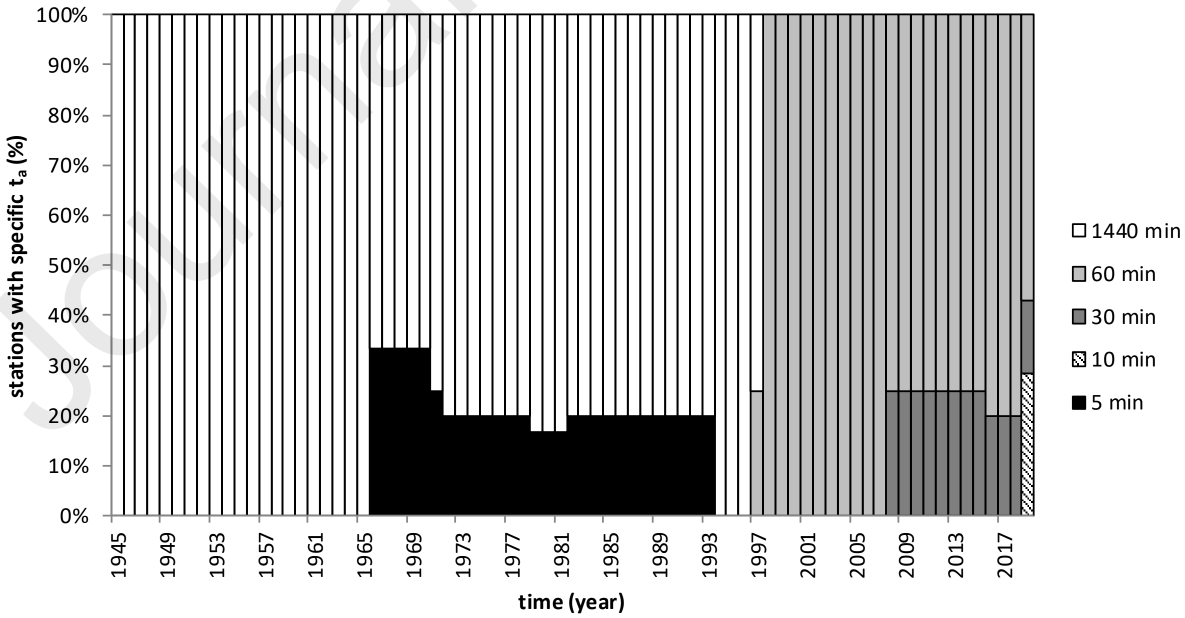


Fig. 21. Percentage of the ITP rain gauge stations in the Kujawsko-Pomorskie region in Poland with specific temporal aggregation, t_a.

3.15 Romania (whole country)

The geographical position of Romania (238400 km²) and the variety of landforms create regional differences in the distribution, quantity and intensity of rainfall. The complex network of pluviometric stations installed in Romania is managed by the National Meteorological Administration (ANM). The available data date back to in 1885, with daily amounts (t_a=1440 minutes); the number of stations has increased over time. At the beginning of the 1900s, there were 27 stations with daily rainfall data, all of them still operative. The first hourly data are available from 1898, but most of the stations were recording by using daily amounts. Figure 22 shows the rain gauge numbers evolution with time. By the end of the 20th century, most of the stations had a time resolution equal to six hours. At the beginning of the 2000s, the National Integrated Meteorological System (SIMIN) project began to operate with automatic weather stations. In 2003 there were 60 automatic stations and, nowadays, all stations in Romania are automatic. This meant a huge quality and quantity upgrade as most of the stations provide data every 10 min, with some exceptions that still involve 60 min amounts (Fig. 23).

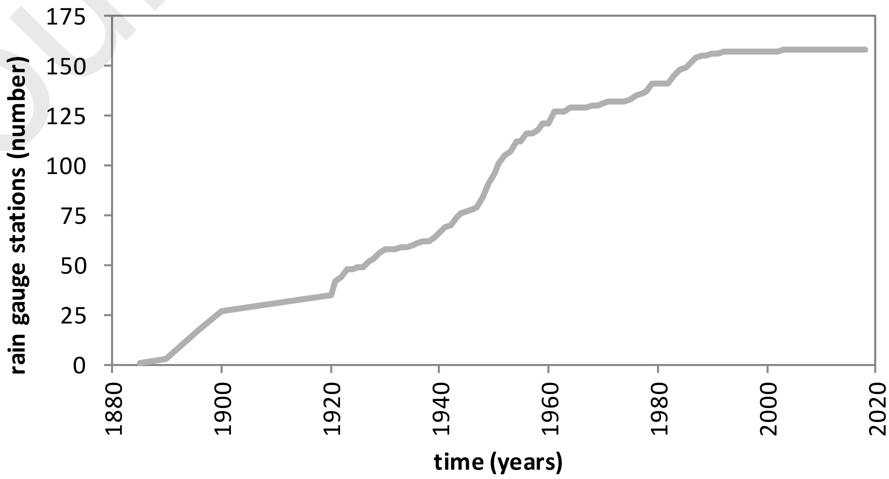


Fig. 22. Rain gauges number evolution with time in Romania

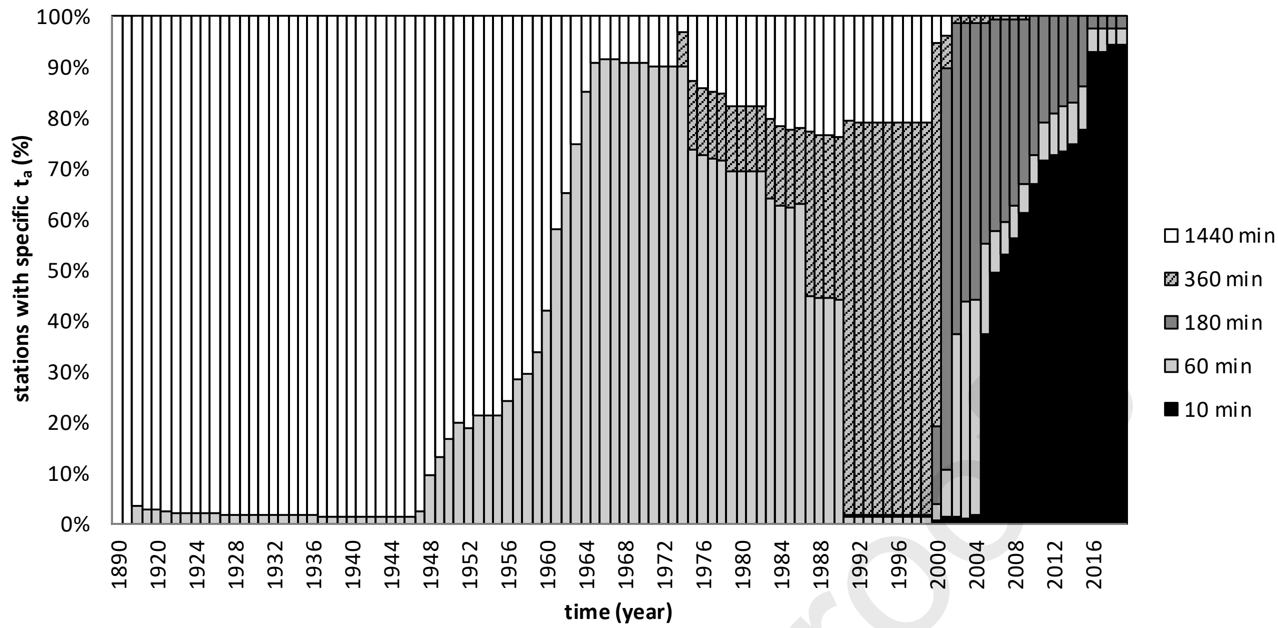


Fig. 23. Percentage of rain gauge stations in Romania with specific temporal aggregation, t_a.

Table 4 shows some representative rain gauge stations divided into two groups: 1) previously manual stations which were replaced by automatic recording and over the years adopted all types of recording (initially t_a=1440 minutes and later digital recording with an increasing resolution over time from t_a=60 minutes to t_a=10 minutes), 2) high mountain stations, above 2000 m a.s.l. of altitude. As showed in Table 4 and mentioned before, there are no manual stations left; in fact, all of them were replaced by automatic stations.

Table 4. Different groups of representative rain gauge stations of Romania with the time evolution of the adopted temporal aggregation, t_a.

Rain gauge station	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]
Previously manual stations which were replaced by automatic recording					
Buzau	*1896/1960*	*1961/1990*	*1991/1999*	*2000/2006*	*2006/2019*
	1440	**60**	**360**	**60**	**10**
Focsani	*1976/2000*	*2001/2001*	*2002/2005*	*2006/2019*	
	1440	**180**	**60**	**10**	
Mangalia	*1928/1963*	*1964/1986*	*1987/1999*	*2005/2019*	
	1440	**60**	**360**	**10**	
Zimnicea	*1943/2000*	*2001/2001*	*2002/2004*	*2005/2019*	
	1440	**360**	**180**	**10**	
High mountain stations					
Calimani Retitis	*1990/2000*	*2001/2004*	*2005/2015*	*2016/2019*	
(2022 m)	**1440**	**180**	**60**	**10**	
Balea Lac	*1979/2000*	*2001/2002*	*2003/2004*	*2005/2018*	

(2070 m)	**1440**	**180**	**60**	**10**	
Varfu Omu	*1927/1974*	*1975/2000*	*2001/2015*	*2016/2018*	
(2504 m)	**1440**	**360**	**180**	**10**	
Tarcu (2180 m)	*1961/1974*	*1975/2000*	*2001/2013*	*2014/2015*	*2016/2019*
	1440	**360**	**180**	**60**	**10**

In addition, almost all-weather stations from NMA functioning from 1961 to 2008 have paper records with sub hourly measurements made with mechanical rain gauge instruments (pluviograph records). The first mechanical recording precipitation gauge was installed at Bucuresti Filaret starting with 1898, and the measurements were made continuously up to the time when the weighing rain gauge was put into place.

3.16 Seoul (South Korea)

The first available pluviometric recordings in Korea date back to the Choson dynasty (1392-1910). The traditional Korean rain gauge, the Chukwooki, was used to measure rainfall in major cities in Korea. This device was invented in 1441, and the longest data available is in Seoul since 1777. The data structure of the Chukwooki rainfall is very basic, with simply the starting time, ending time, and the total rainfall depth of a rainfall event. That is, only the duration and total rainfall depth of a rainfall event were recorded (Yoo et al., 2015).

The modern rain gauge in Seoul was installed in 1907. Originally, the measurement was made only three times a day, i.e., with t_a=480 minutes. The first rain gauge with registration on paper rolls was installed in 1915. Since then, the measurement interval became equal to 240 minutes (from 1921 to 1939), 180 minutes (from 1940 to 1960) and 60 minutes (from 1961 to 1999). The first station equipped with digital data-logger came into operation in 2000. Currently the measurement interval of the rain gauge in Seoul is 1 minute (i.e., t_a=1 minute).

3.17 Andalusia region (Southern Spain)

This region occupies almost 88000 km^2 and is located in the south-western Europe (south of Spain), with the singularity of having the Mediterranean Sea and the Atlantic Ocean, southeast and southwest, respectively.

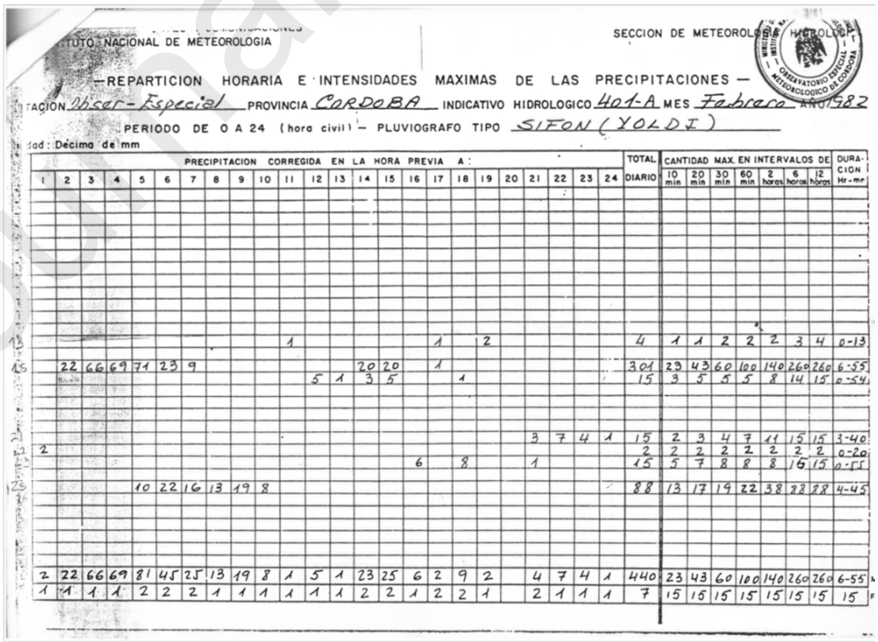
There are several networks of meteorological observatories that provide precipitation data. However, validated datasets are scarce due to the non-application of quality assurance procedures (Estévez et al., 2011). The oldest network is managed by the Agencia Estatal de Meteorología (AEMET), organization that provides meteorological services throughout the Spanish territory, with a total of 1914 manual, 28 semi-automatic and 42 automatic stations. At the end of the 1990s the Department of Agriculture and Fisheries of the Regional Government started to manage the Agroclimatic Information Network (RIA) and the Phytosanitary Information Alert Network (RAIF), with 89 and 81 automatic stations, respectively. Furthermore, about a decade ago, the Department of Environment of the Regional Government started managing the Network to fight forest fires (INFOCA) with 32 automatic stations and the Network of Surveillance of the quality of the Air (SIVA) with 43 automatic stations. Finally, there are two more networks called Automatic Hydrological Information Systems, one located in the Guadalquivir basin and the other in the Mediterranean basin.

In summary, only three networks have active rainfall stations with significant time-periods: AEMET, RIA and RAIF. The RIA network provides daily values (t_a=1440 minutes) from 1999-2000 and semi-hourly values (t_a=30 minutes) since 2002 at all stations. The RAIF network provides daily (t_a=1440 minutes) and hourly (t_a=60 minutes) records since 1996 at all stations. The AEMET network provides daily (t_a=1440 minutes) records at all stations, hourly records (t_a=60 minutes) at main automatic stations and ten-minutes records (t_a=10 minutes) at only certain stations.

For these last stations, available data from automatically recorded AEMET vary according to the temporal resolution. Hourly data are available from 1980 for Málaga airport, from 1997 for Córdoba airport and Huelva, and from 1998 for Cádiz. Manually recorded hourly data are also available at these station from the early 1980s. Figure 24 shows a manual registration of hourly rainfall data at Córdoba airport station in February 1982. As it can be seen, the records also show the daily total amount of rainfall and the maximum rainfall registered for several durations (from 10 minutes to 12 h).

Data from the National Bank of Climatic Data were collected and validated by AEMET, and as a result 10-min resolution rainfall data are also available since 2009. For the same time resolution there are also rainfall data registered since 1998, but these data were recorded by regional organizations and were not included in the AEMET data base.

In recent works, precipitation datasets from some of these stations have been used as quality records for different characterization analysis (García-Marín et al., 2015; Medina-Cobo et al., 2017) and to develop new validation procedures for rainfall data (Estévez et al., 2015).



...TUTO NACIONAL DE METEOROLOGIA

SECCION DE METEOROLOGIA HIDROLOGICA

—REPARTICION HORARIA E INTENSIDADES MAXIMAS DE LAS PRECIPITACIONES —

...TACION Obser-Especial PROVINCIA CORDOBA INDICATIVO HIDROLOGICO 401-A MES Febrero AÑO 1982

PERIODO DE 0 A 24 (hora civil) — PLUVIOGRAFO TIPO SIFON (YOLDI)

...dad: Decima de mm

	PRECIPITACION CORREGIDA EN LA HORA PREVIA A:																								TOTAL	CANTIDAD MAX. EN INTERVALOS DE							DURACION
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	DIARIO	10 min	20 min	30 min	60 min	2 horas	6 horas	12 horas	Hr-mn
13											1						1		2						4	1	1	2	2	2	3	4	0-13
15		22	66	69	71	23	9							20	20		1								301	23	43	60	100	140	260	260	6-55
												5	1	3	5			1							15	3	5	5	5	8	14	15	0-54
21																					3	7	4	1	15	2	3	4	7	11	15	15	3-40
22	2																								2	2	2	2	2	2	2	2	0-20
23																6		8			1				15	5	7	8	8	8	15	15	0-55
25					10	22	16	13	19	8															88	13	17	19	22	38	88	88	4-45
	2	22	66	69	81	45	25	13	19	8	1	5	1	23	25	6	2	9	2		4	7	4	1	440	23	43	60	100	140	260	260	6-55
	1	1	1	1	2	2	2	1	1	1	1	1	1	2	2	1	2	2	1		2	1	1	1	7	15	15	15	15	15	15	15	15

Fig. 24. Manual registration of rainfall values at Cordoba station (Andalusia, Spain).

3.18 Catalonia and Barcelona city (northestern Spain)

The pluviometric stations of the Catalonian territory (approximately 32000 km²) considered in this study are managed by the Meteorological Service of Catalonia (SMC). Their available data began in 1855, with daily amounts (t_a=1440 minutes) measured in a station located in the old building of the University of Barcelona in the center of the city (Convent of Carmen). Through the 1910s, the number of stations increased to around one hundred, some of them still operative at present. For instance, the data from the Ebre Observatory have almost 115 years of daily data (from January of 1905) with only a small single period of interruption of few months of 1938 in the middle of the Spanish Civil War (1936-1939). Daily data from the Abbey of Montserrat, also currently operational, began even earlier, in 1901; and in the Fabra Observatory of Barcelona data started from 1913. The first pluviographs were installed along the 1920s; for instance, the innovative Jardí intensity rain gauge located in the Fabra Observatory of Barcelona began to work in 1927. Meanwhile, the number of stations distributed throughout the territory continued to increase. This number decreased drastically during the Spanish Civil War, and did not recover until the next decade. Figure 25 shows the rain gauges number evolution with time.

The measurement of precipitation took a qualitative leap when it began to be performed at a higher resolution than the daily one in the last decades of the 20th century. The SMC Network of Automatic Meteorological Stations (XEMA) began to operate with digital data-loggers in 1988. This network, along with the Automatic Hydrological Information System (SAIH), put into operation in 1996, and the SMC Meteorological Observers Network (XOM) starting in 2009, began to provide hourly (t_a=60 minutes) and semi-hourly (t_a=30 minutes) records. Currently, all the XEMA stations provide data with t_a=1 minute (Fig. 26), except for a few high mountain stations which remain working with t_a=30 minutes. A quality control of the whole SMC available precipitation dataset was recently performed by Llabrés-Brustenga et al. (2019).

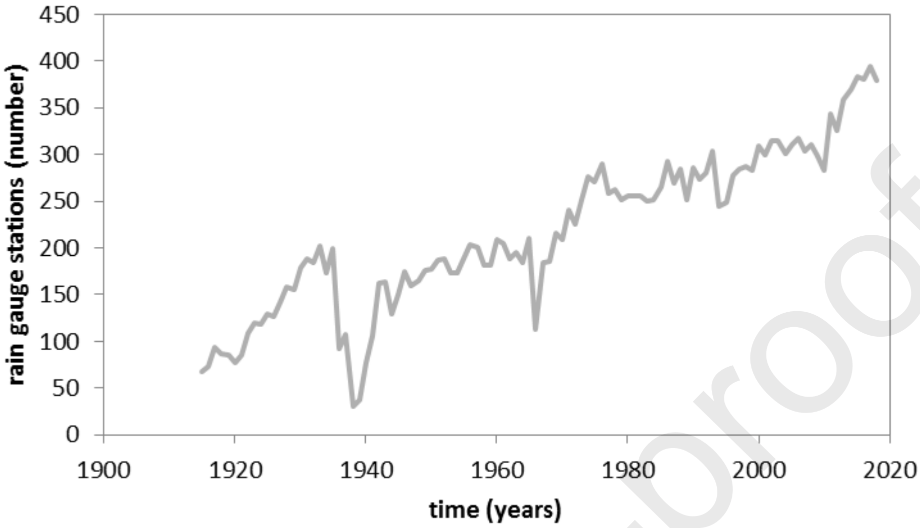


Fig. 25. Rain gauges number evolution with time in Catalonia (northeastern Spain).

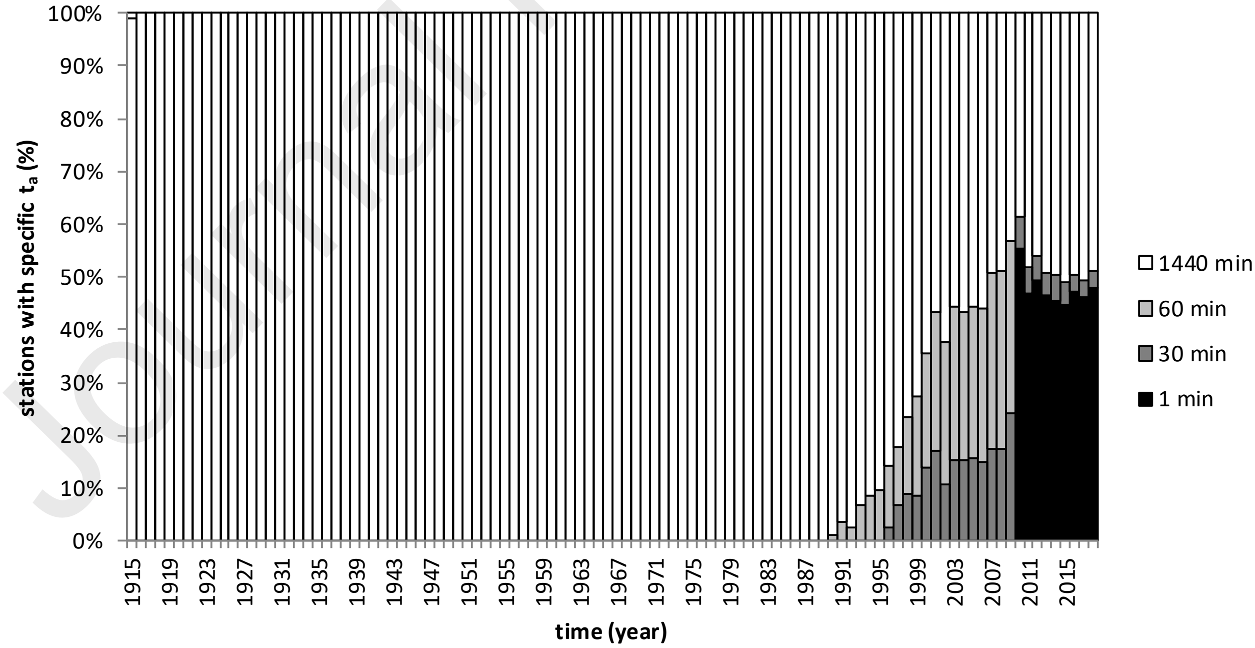


Fig. 26. Percentage of rain gauge stations in Catalonia (northeastern Spain) with specific temporal aggregation, t_a.

Table 5 shows some representative rain gauge stations for four different groups of stations: 1) very old manual stations still operational in the present with t_a=1440 minutes, 2) previously manual stations which were replaced by automatic recording and over the years adopted all types of recording (initially t_a=1440 minutes and later digital recording with an increasing resolution over time from t_a=60 minutes to t_a=1 minute), 3) automatic stations, some of them starting with a resolution of 60 and 30 minutes later increased to 1 minute in the process of homogenization of the network performed by the SMC in the first decade of the 21st century, some of which installed after 2008 with a resolution of 1 minute since the beginning, and finally, 4) high mountain stations, above 2000 m of altitude a.s.l., equipped with special automatic gauges which remain with a maximum resolution of 30 minutes due to the characteristics of their environment.

Tab. 5. Different groups of representative rain gauge stations of Catalonia (northeastern Spain) with the time evolution of the adopted temporal aggregation, t_a.

Rain gauge station	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]	*From/To* [year] t_a [minutes]
Very old manual stations still operational				
Ebre	*1905/2019*			
	1440			
Fabra	*1914/2019*			
	1440			
Montserrat	*1902/2019*			
	1440			
Cadaquès	*1911/2019*			
	1440			
Previously manual stations which were replaced by automatic recording				
Vielha	*1946/1992*	*1998/2009*	*2010/2019*	
	1440	**30**	**1**	
El Pont de Suert	*1946/1998*	*1999/2009*	*2010/2019*	
	1440	**30**	**1**	
Organyà	*1951/1998*	*1998/2009*	*2010/2019*	
	1440	**30**	**1**	
Oliana	*1951/1997*	*2001/2009*	*2010/2019*	
	1440	**60**	**1**	
Automatic stations since the beginning				
Raimat	*1990/2009*	*2010/2019*		
	60	**1**		
Sant Pere Pescador	*1991/2009*	*2010/2019*		

	60	**1**	
Amposta	*1993/2009*	*2010/2019*	
	60	**1**	
Constantí	*1993/2007*	*2008/2009*	*2010/2019*
	60	**30**	**1**
high mountain stations			
Boí	*2002/2008*	*2009/2019*	
(2535 m asl)	**60**	**30**	
Sasseuva	*2005/2008*	*2009/2019*	
(2228 m asl)	**60**	**30**	
Malniu	*2006/2008*	*2009/2019*	
(2230 m asl)	**60**	**30**	
Cadí Nord	*2006/2008*	*2009/2019*	
(2143 m asl)	**60**	**30**	

3.19 Madrid (Spain)

The Madrid station considered in this study is located in the Retiro Park of the city. It is an emblematic station with more than a century of observations (Casas-Castillo et al., 2018), the first one of the networks managed by the state meteorological agency AEMET. The precipitation dataset available for this study began in 1920, with daily measures (t_a=1440 minutes). In 1997 the data resolution increased to 10 minutes due to the installation of an automatic device, as in others stations of the AEMET network in that decade.

3.20 San Fernando (southern Spain)

The particular case of the observatory of San Fernando stands out, in the global framework of the observatories of Spain, for the quality and continuity of its meteorological series, including daily data of precipitation, temperature, atmospheric pressure and humidity. Thus, it is considered as a reference observatory, due to the homogeneity of its temporal series, which is the longest of south Spain (Rodrigo, 2002). The data from the observatory of San Fernando –between the late 18th century and early 19th century– were affected by changes in the location of its facilities and the years of war against the Napoleonic troops. It is also worth mentioning that the Royal Spanish Navy did not consider meteorological observations a priority activity until 1870-1876 (Barriendos et al., 2002).

The first records of precipitation correspond to the year 1805. Between 1805 and 1836, the recordings were halted for several days to measure the rainfall, thus, despite the existence of data, the t_a was >1440 minutes. From 1837, the measurements can be taken into account, since the t_a was equal to 1440 minutes.

3.21 Uppsala County (eastern Sweden)

The Swedish Meteorological and Hydrological Institute (SMHI) is the main agency responsible for meteorological measurements and forecast in Sweden and currently manages ~650 rain gauge stations distributed all over the country (https://www.smhi.se/data/meteorologi/nederbord). In this study, we exemplified the Swedish case with data from the Uppsala County, one of the 21 administrative regions in Sweden, which covers an area of 8207 km^2 in the central-east part of the country. Consistent precipitation records here are available since as early as 1893 from the weather station at Örskär, a small island north of the coastal town of Öregrund. This was the only recording station in the Uppsala region until after the Second World War, when SMHI added 18 stations in 1945 (records at Örskär stopped between 1919 and 1948, both included). Since then, the number of stations has fluctuated between 17 (current number) and 26 (reached in 1961) (Fig. 27). As many as 47 stations were operative at some period in the past and are not currently active.

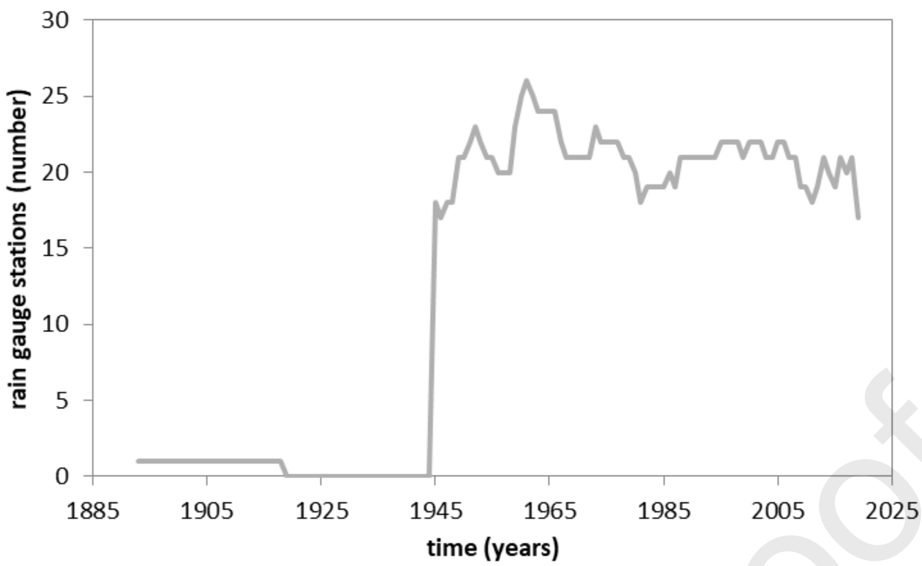


Fig. 27. Evolution of the number of precipitation stations managed by the Swedish Meteorological and Hydrological Institute in the Uppsala County, eastern Sweden.

Most SMHI station measurements in Uppsala County (and in general in Sweden) were and are still currently made manually. An observer records the amount of precipitation accumulated in calibrated aluminium collectors once per day (thus t_a=1440 minutes in most cases). The first automatic station in the study region was established in 1986 in the city of Uppsala, providing records every hour (t_a=60 minutes) and it is still operational. Currently, there are six automatic stations, three providing records every hour (t_a=60 minutes) and three providing records every quarter of an hour (t_a=15 minutes) (Fig. 28). It should be noted that part of the precipitation in this area falls as snow and this entails specific challenges and logistics as compared with precipitation stations that only record rainfall. A transition into a t_a=1 min is currently undergoing at SMHI for the automatic stations.

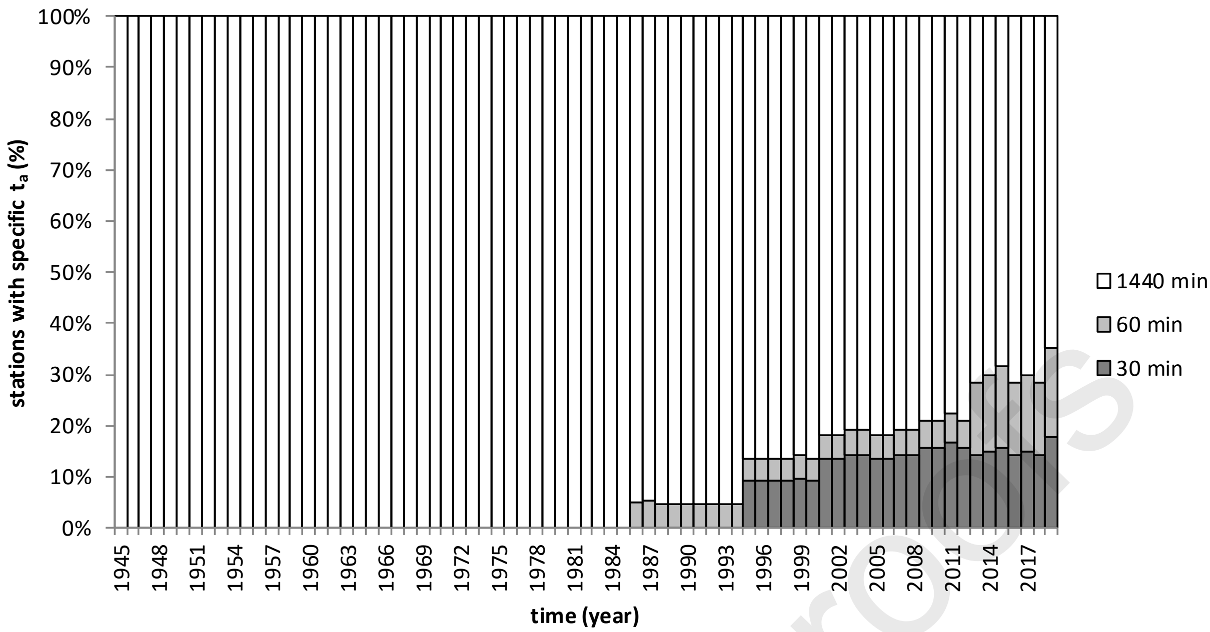


Fig. 28. Percentage of precipitation stations in Uppsala County (eastern Sweden) with specific temporal aggregation, t_a, in the period from 1945 to now.

3.22 United States of America (whole country)

Rainfall gauge measurements over the USA are characterized by a high level of heterogeneity among the different networks that serve the entire country or specific States for multiple purposes, using different t_a and network density.

A major conceptual distinction that was inherited from the past, can be made among voluntary vs not-voluntary networks, also called in the past as networks of first (carried on as a national effort) and second order (based on a volunteer effort), respectively. These networks have been developed from the past throughout the years by the US governments and different associations in precipitation measuring.

The first order network is carried on by a national centralized effort with national coverage and high technological stations, while the second order observation networks developed as a complementary service that was carried on as a cooperative and volunteering based effort. Even today the volunteer-based effort is carried on in some of the networks providing a complementary information to the national networks.

The history of rain measurements evolved following the progressive expansion of people and urbanization from East to West, with the first measurements started spontaneously from the intellectual people of the time, such as Thomas Jefferson and Benjamin Franklin and from institutions with their own "ancestral" networks such as the Surgeon General (operating approximately from 1800s to 1870s) and the Smithsonian Institution (from about 1847 to 1874).

The first official weather service was established when the Congress passed 1870 a joint resolution signed by President Ulysses S. Grant to "provide for taking meteorological observations at the military stations in the interior of the continent and at other points in the States and Territories ... and for giving notice on the northern (Great) Lakes and on the seacoast by magnetic telegraph and marine signals of the approach and force of storms." In that occasion the Weather Bureau of the United States was established and only in 1970 it was called the National Weather Service.

At the beginning of the recording history, the observations were made manually at the daily scale, using 8 inches rain gauges. In the 1990s the tipping bucket system was introduced. These tipping buckets were found to under-catch during high intensity rainfall events and were replaced with all-weather accumulating precipitation gauges between 2003-2006, which use a high frequency vibrating wire to record precipitation.

Nowadays in the US each network has a different provider and multiple sponsors are sometimes cooperating for the maintenance and data distribution of the same network. A useful tool in this research was given by the Historical Observing Metadata Repository (https://www.ncdc.noaa.gov/homr/#) as distributed by NOAA-NCEI (National Center for Environmental Information). This institution provides an integrated station history, metadata and very detailed information and documentation both at the single site level and at the overall network level.

In the following some details are given about the main networks, and Table 6 provides a synthesis of them in a more schematic way.

The National Weather Service - Cooperative Observer Program (NWS-COOP) currently is a network of 8700 volunteers that take observations at multiple locations across USA (farms, in urban and suburban areas, National Parks, seashores, and mountaintops). The historical network is composed of more than 33,000 stations. The most common precipitation gauge is the non-registering 8" Standard Rain Gauge (SRG) that records daily precipitation. In addition to that, they also use recording gauges, such as the Fisher/Porter (F&P), consisting of a load cell and a datalogger to record precipitation with t_a=15 minutes.

The Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) is a non-profit and community-based network that is based on volunteers that take measurements of precipitation using low-cost measurement tools. The network comprises around 10,000 stations, adopting t_a=1440 minutes and using 4" Rain gauges.

The U.S. Climate Reference Network (USCRN) has the main aim of providing the best possible measurements to serve as a benchmark source of climate data for the United States. The stations of this network are very accurate and consistent over the years but the average density over the country is about one station each 265 km^2. This resolution can give appropriate information to study climate trends but it is not able to detect convective systems. Rainfall is measured with a Geonor T-200B precipitation gauge, a weighing precipitation device equipped with three high frequency vibrating wires to record precipitation with t_a=5 minutes.

The U.S. Regional Climate Reference Network (USRCRN) is a pilot project network designed to give the same temperature and precipitation information as USCRN but at a resolution of about 130 km^2 in order to provide detection of regional climate signals. The project started in the southwest but at the moment it is suspended, with about 538 locations in the USA measuring in the period 2009-2011. Precipitation measurements are done using the same methods and time resolution as USCRN.

The Automated Surface Observation System (ASOS) is a suite of sensors used to record weather elements at all major and most minor airports. This network is owned by NOAA, FAA and DOD. The network was originally deployed in the middle 1990s with a heated tipping bucket, but then it transitioned to Geonor Weighing Rain Gauge (AWPAG) over a period of time (2003-2006). Even though the transition occurred over time, t_a always remained equal to 15 minutes.

The Automated Weather Observing System (AWOS) stations are mainly operated by state or local governments and other non-Federal entities and are certified under the FAA Non-Federal AWOS Program. The sensor is of tipping bucket type and precipitation is recorded every 20 minutes at 15, 35 and 55 minutes after the hour.

In the Supplementary Material (click here) of this paper, as well as in Table 6, detailed information regarding the t_a history in the US only refers to the Colorado State.

Table 6. Main rain gauge networks in Colorado (US), with the approximate total number, the order (voluntary or not) and the adopted temporal aggregation, t_a.

Network Name	N. Stations (in the USA)	Voluntary	t_a (minutes)
NWS-COOP	33,000	Yes	15/1440
COCORAS	10,000	Yes	1440
USCRN	130	No	5
USCRNR	538	No	5
ASOS	900	No	1/15
AWOS	1100	No	20

4. Discussion

Hydrological monitoring activities have always considered the need of long hydrological records for water resources planning, flood estimation and understanding the involved processes. Recently, however, an increasing need has emerged for long-term datasets to deduce how hydrological regimes are responding to climatic variations and anthropogenic influences.

Whilst climate models can inform us about expected impacts of global changes, the validation of these models requires real data. More importantly, society needs to know the impact of the changes at the national and catchment levels and identify emerging trends or changes in hydrological regimes at these scales. This can only be done by assessing long-term records that capture the natural variability.

Even though the collected data do not perfectly cover all the countries of the world they are sufficiently representative of many geographical areas and, in any case, represent the first database ever realized for the time-resolution of rainfall data. The absence of stations from large countries such as, f.i., Russia, Germany, France and United Kingdom, could be successively filled.

As it can be seen in the database (shown in the Supplementary Material – click here), only in a few cases the series of rainfall data started in the 19th century (e.g. 1881 in Nicosia-Cyprus), while most began in early 20th century (e.g. 1916 in Tuscany-central Italy, 1945 in Argentina). For each study area the main characteristics (total series length and adopted t_a interval) of the longest record are shown in Fig. 29. As it can be seen, in some cases the t_a history of stations operating for over 200 years has been reconstructed, although in most study areas the longest series characterized by known t_a history was about 100 years. Furthermore, only in a few study areas the t_a history is available for stations recently installed.

In almost all study areas, particularly when the rain gauge networks are very dated, recordings started in manual mode (Table 7) with a coarse time resolution, normally equal to 1 day (f.i. in Romania), but in some cases equal to 1 month (f.i. in the Kujawsko-Pomorskie Polish region) or to 1 year (f.i. in the Achna rain gauge station, Cyprus). The oldest manual data recording included in the database are characterized by t_a equal to several days in the San Fernando station (Spain from 1805), and t_a equal to 1440 minutes in Parramatta station (Australia from 1832).

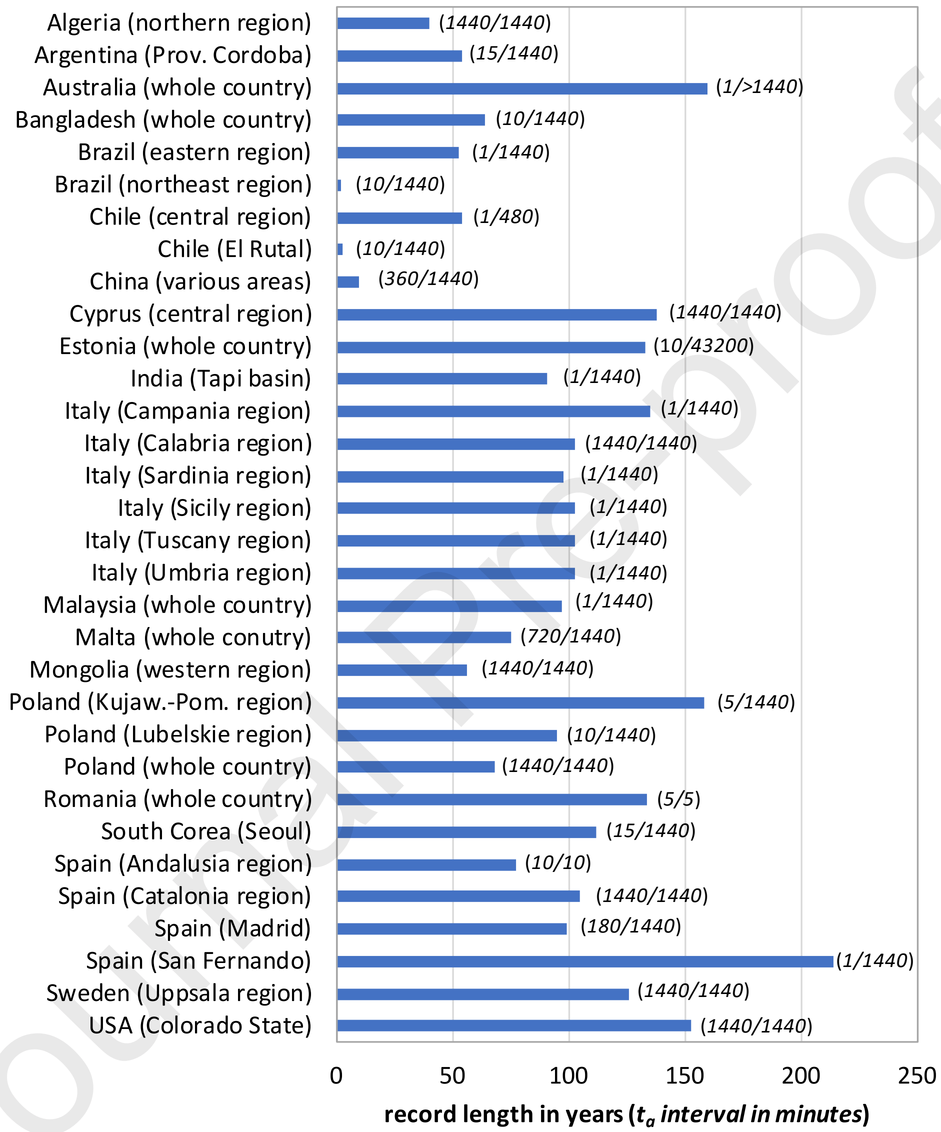


Fig. 29. Total length and adopted t_a interval (minimum/maximum) of the longest record of each study area considered in the database.

Table 7. Year of beginning for manual, mechanical and digital rainfall recordings for the study areas considered in this analysis.

Country (Area)	Beginning of manual recording [year]	Beginning of mechanical recording [year]	Beginning of digitized recording [year]

Algeria (northern region)	1942	1967	-
Argentina (Prov.Córdoba)	1941	1941	1985
Australia (whole country)	1826	1920	1989
Bangladesh (whole coun.)	1867	1948	2003
Brazil (eastern region)	-	1965	-
Brazil (northeast region)	-	-	2016
Chile (El Rutal)	-	-	2011
Chile (central region)	-	1959	2012
China (various areas)	-	-	2006
Cyprus (central region)	1881	1911	2003
Estonia (whole country)	1860	-	2009
India (Tapi basin)	1925	1969	2012
Italy (Campania region)	1884	1921	2007
Italy (Calabria region)	1916	1916	1989
Italy (Sardinia region)	1921	1927	2007
Italy (Sicily region)	1832	1916	2002
Italy (Tuscany region)	1916	1928	1991
Italy (Umbria region)	1915	1928	1986
Malaysia (whole country)	-	1972	-
Malta (whole country)	1922	1957	2006
Mongolia (western region)	1963	-	2014
Poland (whole country)	1951	1963	2005
Poland (Kujaw.-P. region)	1861	1966	1997
Poland (Lubelskie region)	1922	-	1994
Romania (whole country)	1885	1898	2000
South Korea (Seoul)	1907	1915	2000
Spain (Andalusia region)	1942	-	1980
Spain (Catalonia region)	1885	1913	1988
Spain (Madrid)	-	1920	1997
Spain (San Fernando)	1805	-	1987
Sweden (Uppsala region)	1893	-	1986
USA (Colorado State)	1872	1948	1992

Apart from exceptional cases, mechanical recordings on paper rolls began in early 20th century, typically with t_a equal to 1 h or 30 minutes. As an example, in the database it can be found the existence of mechanic recordings carried out in the Alghero station (Italy-Sardinia region) from 1927 and in the Campulung station (Romania) from 1949, in both cases with t_a=60 minutes.

Digital data logging began in the last decades of the 20th century with the consequence that analyses of the effects of climate change on short-duration (sub-hourly) heavy rainfalls appear virtually undetectable in almost all geographical areas of the world; today the percentage of stations with data available at any time resolution (that is practically t_a=1 minute) is very high. Examples of digital data characterized by t_a=1 minute can be found in the Borgo S. Lorenzo station (Italy-Tuscany region) from 1991 and in the Valletta station (Malta) from 2006.

From the description of the rain gauge networks provided in the previous section, it comes out a marked heterogeneity of situations, each conditioned by the specific politico-cultural history of the corresponding country.

It is difficult to synthesize in individual figures and tables the descriptions referred to all the study areas as they sometimes contain and summarize the history of a single rain gauge, such as in the case of the station installed in Madrid (section 3.19), whereas in other cases they refer to a network with thousands of rain gauges, such as in the case of Australia (section 3.2) and United States (section 3.22). Despite this difficulty, Fig. 30 provides an interesting synthesis on the percentage of rain gauges with specific t_a for all the stations included in the database (see also the Supplementary Material – click here) except those located in Australia and Colorado (United States). In fact, due to the high number of stations in the database for Australia and Colorado, equal to 17,768 and 5732, respectively, a comprehensive analysis would be misleading. Figure 30 highlights that today, owing to the ease of continuous data recording, about 50% of the stations in the database (excluding those in Australia and Colorado) are working with t_a=1 minute. The data recording with t_a=1440 minutes will disappear within a short period.

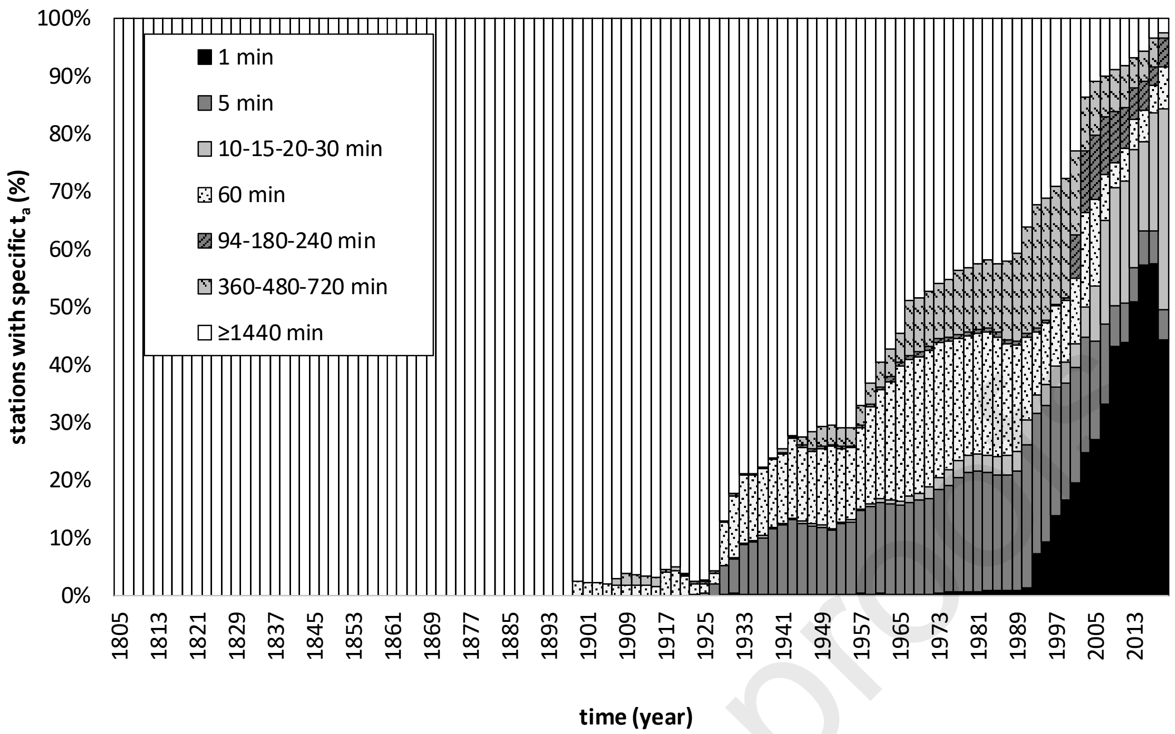


Fig. 30. Percentage of rain gauge stations with specific temporal aggregation, t_a, for all stations included in the database (see also the Supplementary Material – click here) except those located in Australia and Colorado (US).

An accurate analysis of both section "Results" and Supplementary Material (click here) also shows that most of the rain gauge stations changed the registration methods over the years. In many cases stations started working with daily manual recordings, then switched to mechanical recorders (t_a equal to 30 minutes or 1 h), more recently paired with digital data loggers capable of continuous recording. In the Supplementary Material (click here), many rain gauge stations with variable t_a over time can be found. It is noticeable that these changes were not perfectly synchronized over the world. Both Table 7 and Fig. 30 show that, in some study areas, systems were updated in a faster way than in others. As an example, in the Gubbio station (Italy-Umbria region) a gradual and efficient change was implemented because rainfall data were recorded manually from 1921 to 1928, mechanically from 1929 to 1991 and automatically from 1992 to the present.

We remark that when many years of rainfall data are characterized by coarse time resolutions, the annual maximum rainfall depths can be potentially underestimated (Hershfield, 1961; Weiss, 1964; Yoo et al., 2015; Morbidelli et al., 2017) and this error can affect any successive analysis (Acquaotta et al., 2019), such as that finalized to verify if extreme rainfalls have been modified by climatic change.

Finally, from the analyses previously described, the evolution with time of the rain gauge number working in some representative study areas (including Argentina, Estonia, different study areas in Italy, Mongolia, Poland, Romania, Spain-Catalonia and Sweden) can be deduced. It should be noted that the number of these stations is not the same reported in the database; in fact, f.i, in section 3.9 hundreds of Sicilian rain gauges are mentioned, while in the database the t_a history of only 18 representative stations is reported. On the same line of the results showed by Mishra and Coulibaly (2009), Figure 31 shows that after many decades of continuous growth of working stations, over the last decade the total number appears to be significantly decreasing, probably due to the high maintenance costs. There is a decreasing trend in the number of pluviometric stations over the years, which indicates negligence on collection of rainfall data. The governments and the agencies responsible for the reduction of funding should not look at instant benefits but rather at long-term benefits deriving from a reduction of water-related disasters. Once the time passes the historical data cannot be recollected again.

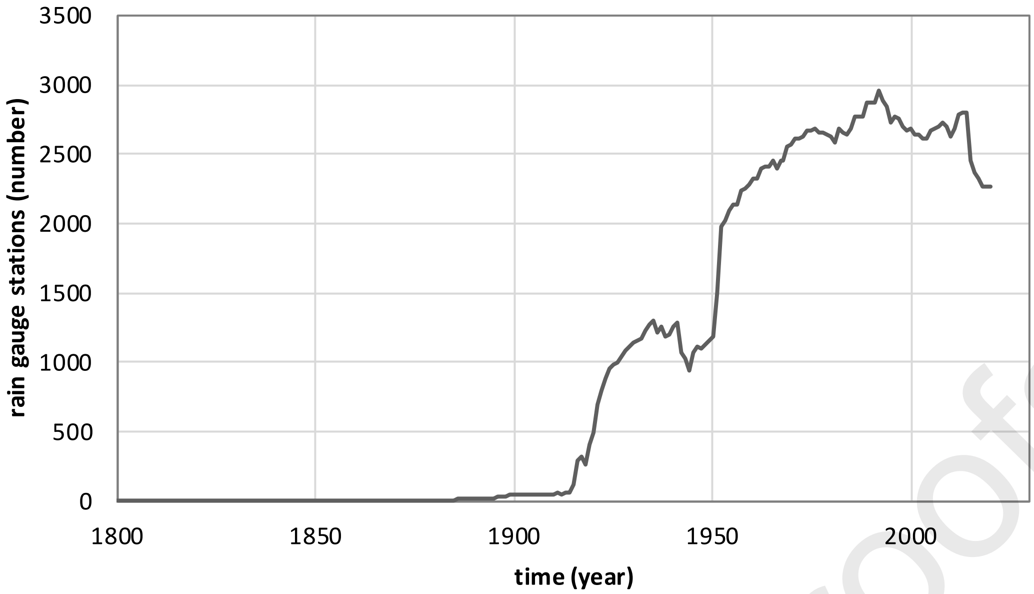


Fig. 31. Evolution with time of the total rain gauge number working in some representative study areas (Estonia, Italy-Calabria, Italy-Sicily, Italy-Tuscany, Italy-Umbria, Mongolia, Poland, Romania, Spain-Catalonia and Sweden).

5. Conclusions

In the world, rainfall data have been observed and recorded by using different temporal aggregations starting from very coarse (e.g. 1 month) and ending to very fine (e.g. 1 minute) values, depending on the adopted rain gauge sensor type and paired data-logger. The marked heterogeneity in the t_a values, dependent on both the specific geographic area and the epoch, can influence subsequent determinations such as intensity-duration-frequency curves or those analyses aimed to evaluate possible effects of climate change on intense rainfall events.

An objective of this paper was to discover and analyze, at global scale, the evolution over the years of the time resolution of rainfall data. Even though the collected outcomes herein do not uniformly cover all geographical areas of the world, they may be considered as representative because the collections involve 25,423 rain gauge stations located in 32 different study areas.

This study provides the first database set up for the time-evolution of the temporal aggregation of observed rainfall data. It is extended to a wide variety of geographic areas and, in addition to the historical information on the rainfall data logging:

- provides the basic elements to perform an improved analysis of extreme rainfalls of different durations using historical series of appropriate length (Papalexiou et al., 2016; Morbidelli et al., 2017);

allows, on the basis of the previous point, a more appropriate comparation of the effect of climate change on short-duration heavy rainfall available on a very large scale in a variety of geographic locations. The presented database enables the scientific community to identify stations for which long H_d series could become available for appropriate design of some hydraulic structures also with regard to possible effects of climate change. Finally, it could stimulate international cooperation in the light to identify appropriate stations for comparative investigations of the effect of climate change on short-duration heavy rainfalls at different spatial scales.

In order to integrate the database, readers of this article are warmly invited to communicate (by contacting the corresponding author of this paper) information on the t_a history of rain gauges networks they manage/know.

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The history of rainfall data time-resolution in a wide variety of geographical areas

Abstract

Collected rainfall records by gauges lead to key forcings in most hydrological studies. Depending on sensor type and recording systems, such data are characterized by different time-resolutions (or temporal aggregations), ta. We present an historical analysis of the time-evolution of ta based on a large database of rain gauge networks operative in many study areas. Globally, ta data were collected for 25,423 rain gauge stations across 32 geographic areas, with larger contributions from Australia, USA, Italy and Spain. For very old networks early recordings were manual with coarse time-resolution, typically daily or sometimes monthly. With a few exceptions, mechanical recordings on paper rolls began in the first half of the 20th century, typically with ta of 1 h or 30 min. Digital registrations started only during the last three decades of the 20th century. This short period limits investigations that require long time-series of sub-daily rainfall data, e.g, analyses of the effects of climate change on short-duration (sub-hourly) heavy rainfall. In addition, in the areas with rainfall data characterized for many years by coarse time-resolutions, annual maximum rainfall depths of short duration can be potentially underestimated and their use would produce errors in the results of successive applications. Currently, only 50% of the stations provide useful data at any time-resolution, that practically means ta=1 minute. However, a significant reduction of these issues can be obtained through the information content of the present database. Finally, we suggest an integration of the database by including additional rain gauge networks to enhance its usefulness particularly in a comparative analysis of the effects of climate change on extreme rainfalls of short duration available in different locations.

KEY WORDS Hydrology history, Rainfall data measurements, Rainfall time resolution

CRediT authorship contribution statement

R. Morbidelli: Conceptualization
All 66 Authors: Investigation, Formal analysis, Writing - original draft, Validation, Methodology, Data curation, Writing - review & editing

1. Available rainfall data are characterized by different time resolution, “ta”

2. A database involving metadata from many geographic areas is presented
3. The "ta" history of rainfall data in a variety of rain gauges is reconstructed
4. The registration methods of the rainfall data changed over the years
5. Currently about 50% of rain gauge stations provide data with any "ta"