A reassessment of the history of the temporal resolution of rainfall data at the global scale

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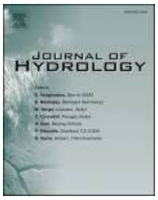

Technical Note

A reassessment of the history of the temporal resolution of rainfall data at the global scale

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ABSTRACT

The availability of rainfall data is of paramount importance in most hydrological studies and is directly dependent on the type of sensors used as well as the recording systems adopted. In fact, these elements have a crucial influence on the temporal resolution (t_a) of stored rainfall data, which in turn affects the types of analysis that can be conducted, making knowledge of t_a on a global scale of particular interest to the entire scientific community and also for engineers. For rain gauges installed more than 70–80 years ago the earliest recordings were manual with coarse temporal resolution. Instead, mechanical recordings on paper rolls began in the early decades of the last century, while digital recordings began only in the last four decades, making analyses requiring long time series of sub-hourly rainfall data impossible. This paper presents a significant update of a previous historical analysis of the time-resolution of t_a (Morbidelli et al., 2020) by which 126,438 stations, located in 77 different geographical areas, were collected into a database, quintupling the number of stations of the previous database and including areas not considered before. It was found that a high percentage of rain gauge stations currently provides useful data at any time-resolution, but there is an increasing development of rainfall networks characterized by very inexpensive, volunteer-operated stations that acquire one data per day ($t_a = 1440$ min), allowing only limited rainfall-related analyses. The invitation for all rain gauge network operators to contribute additional data to the database remains open.

1. Introduction

Rainfall data provide the basis for almost all hydrologic assessments (Wilhelm et al., 2019) and mainly come from ground-based radars, satellites, and rain gauges. Radars installed on the ground can provide an estimate of the phase, amount, and elevation of generic hydrometeors in the atmosphere (Fread et al., 1995; Seo, 1998). Satellites can provide visual and thermal images as well as radiometer platforms to obtain the quantity and phase of hydrometeors (Sorooshian et al., 2000; Joyce et al., 2011). However, only rain gauges located at ground level provide accurate and reliable direct point measurements of precipitation at the earth surface.

Direct observations of rainfall may not always be automatically recorded (Strangeways, 2010). Non-recording gauges are generally provided by top-open vessels in which the rainfall depth is determined by human observation through a graduated scale, while recording gauges are devices that automatically record precipitation at specific time intervals, or at a certain volume of rainfall.

The last category includes the very common rain gauges with tipping buckets, in which rainfall first fills one bucket, which becomes unbalanced, directing the flow of water into the second bucket. The tipping motion of the buckets transmits data to the recording device, allowing precise measurement of precipitation amount and intensity.

When rainfall depth was recorded through direct observation by an operator, only the accumulated amount of precipitation, typically over the past 24 h, was manually transcribed. Whereas, with the introduction of automatic records, initially on paper rolls (e.g., Deidda et al., 2007) and then on digital media, rainfall information at higher time-resolutions (or temporal aggregations), t_a, became possible. Therefore, archived rainfall data are characterized by different t_a values, primarily influenced by the evolution of recording systems and the interest of the data manager.

A variety of studies have investigated the influence of coarse temporal resolutions on the evaluation of annual maximum rainfall depths, H_d, with given duration, d (Hershfield, 1961; Weiss, 1964; Huff and Angel, 1992; Van Montfort, 1997; Young and McEnroe, 2003; Yoo et al., 2015; Papalexiou et al., 2016; Morbidelli et al., 2017; Llabrés-Brustenga et al., 2020; Mazzoglio et al., 2024). For example, Morbidelli et al. (2017) clearly showed that, for durations comparable to the temporal resolution of the measurements, the actual H_d value can be underestimated by up to 50 percent. Moreover, long H_d series always include a high percentage of elements derived from rainfall data with coarse t_a, thus containing underestimated values, along with a considerable percentage of H_d values obtained from continuous data (with $t_a = 1$ min) recently recorded with digital systems. This issue, as well as the relocation of stations, the use of different types of rain gauges over time, and changes that have occurred around the rain gauges, could produce significant effects on many derived analyses, including the evaluation of rainfall depth-duration-frequency curves (Morbidelli et al., 2017) and trend estimates for extreme precipitation (Morbidelli et al., 2018).

Underestimation of maximum annual rainfall depths could be solved by using one of the methods available in the scientific literature (Hershfield, 1961; Weiss, 1964; Morbidelli et al., 2017; Llabrés-Brustenga et al., 2020), based on the use of relationships to determine the mean error as a function of the duration of interest and t_a. Nevertheless, it can be easily concluded that the temporal resolution of rainfall data also affects the type of analysis that can be performed. For instance, it is very difficult to analyze long H_d series for durations shorter than 1 h because, for most regions of the world, continuous rainfall data are only available for the last few decades.

Considering a global scale, Morbidelli et al. (2020) analyzed the evolution over the years of the temporal resolution of rainfall data. They collected data from 25,423 rainfall stations located in 32 different study areas, resulting in the first database created for the evolution in time of the temporal aggregation of observed rainfall data. The database evidenced that a large number of stations presented time series that should be adjusted for their use in the analysis of extreme precipitation of different durations. Furthermore, it can also be used to reduce bias in statistical analysis, facilitating comparative investigations of the effects of climate change on short-duration intense precipitation.

One of the objectives of Morbidelli et al. (2020) was to engage the readers of the article to integrate the above mentioned database with information related to other stations since the estimated number of rain gauges in the World should be between 150,000 and 250,000 (Strangeways, 2007). After 4 years from that call, there are many researchers who have joined the initiative and shared their metadata. In addition, a network of hydrologists working within the IAHS HELPING group "REHYDRATE – REtrieve historical HYDRologic dATa & Estimates" have also been involved in this project.

The main objective of this paper is to update the work of Morbidelli et al. (2020), including the history of the rainfall data time-resolution of stations located in region of the world not previously considered, contributing to the production of a comprehensive and exhaustive database.

2. Materials and methods

2.1. Overview on the temporal evolution of rainfall stations

Although it was predicted that radar and satellite would make automatic rain gauge measurements redundant (Kurtyka et al., 1953), they remain important, especially in regions with limited infrastructure but well-developed rain gauge networks (Kidd et al., 2017).

The measurement of precipitation and recording procedures have been progressively improved since the beginning of the scientific revolution, when naturalists understood the importance of the availability of rainfall data. Despite significant challenges, efforts were made as early as the 1700 s to limit wind-related measurement errors, and regular daily records were encouraged (Wolf, 1961).

The adoption of rain gauges expanded alongside the development of the meteorological profession in the second half of the 19th century. At that time Symons (1869) developed many of the technical and statistical methods for collecting and analyzing rainfall data useful in global practice, providing suggestions that for the first time guided technicians and scientists (Anderson, 2005; Strangeways, 2007).

The most important developments in rainfall sensor design and data recording techniques occurred at the turn of the 19th and 20th centuries. Although manual recording remained in use for several decades, automatic recording devices were introduced as early as the 1860 s and 1870 s. Moreover, the adoption of the famous German automatic Hellmann siphon rain gauge dates back to 1897, followed later by the rain gauge designed by the U.S. Weather Bureau and the British rain gauge based on Symon's model.

In the same years, with the founding of the International Meteorological Organization (which took place in 1873), the first efforts to standardize rainfall measurements began, continued many years later by the World Meteorological Organization (WMO), established under the United Nations in 1950 after the signing of the 1947 World Meteorological Convention. Despite the efforts to standardize the measurement and recording of rainfall, more than 50 different types of rain gauge used globally were counted by the end of the 20th century (Sevruk and Klemm, 1989). This diversity has been identified as a major problem in the act of comparing rainfall data observed in different geographical areas of the planet (Goodison et al., 1998; Pollock et al., 2018).

2.2. Temporal evolution of ground rainfall data

Initially, until the first decades of the last century, most rainfall data had a daily resolution, recorded manually every day at the same local time (see Fig. 1).

Until the advent of digital data loggers, rainfall data were recorded only on paper rolls, from which data with $t_a = 30$ min or 1 h could then be easily derived (see Fig. 2), although ink pens worked continuously and so the resolution might have been even smaller.

Today, rainfall on the ground is generally measured with tipping bucket sensors that, when coupled with digital data loggers (Fig. 3), allow the adoption of any aggregation time interval. It is then up to the managers of the instrument to decide how to store the data, also depending on the objective they need to pursue.

2.3. The new t_a database

After the publication of the paper by Morbidelli et al. (2020), many scientists provide historical information about rainfall measurement (including the temporal resolution) from as many rain gauges as possible, typically located in the geographic areas where they live and/or work.

While the database by Morbidelli et al. (2020) contained the history of 25,423 rain gauges, located in 32 different regions, about 100,000 more were added for the new database, for a total of 126,438 (see also Table 1), overall located in 77 different areas (as shown in Fig. 4). Therefore, in this new paper the rain gauges considered have more than quintupled and, more importantly, it has been possible to include the t_a history of rain gauges placed in areas never considered before.

For each area included in this study, further details on the t_a histories of selected stations can be found in the next section (Results).

Although the number of stations included in this database has increased significantly since Morbidelli et al. (2020), it has not yet been possible to include stations from some countries such as Germany and France. However, it has been noted that in Western European countries, the evolution over the years of the temporal aggregation of rainfall data has occurred almost everywhere in the same way, regardless of the specific country. Therefore, it can be said that what occurred in Italy and Spain (for both these countries a lot of information is available) can be considered quite similar to what presumably occurred in other European countries.

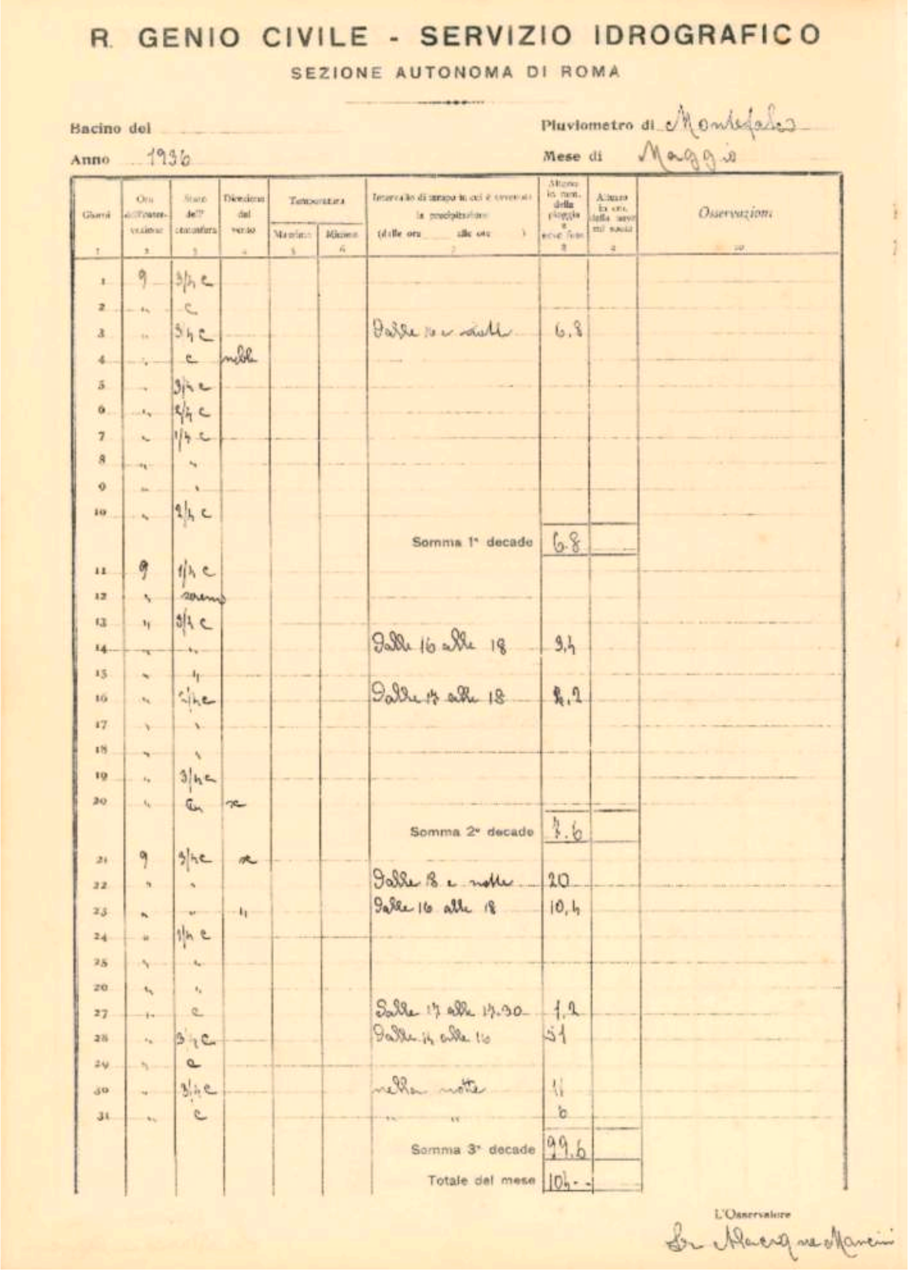
The database, containing detailed rainfall time resolution data, is available in *.xlsx format (see Fig. 5) as part of the Supplementary Material (click here). Alternatively, it can be requested from the corresponding author of this paper.

3. Results

This section provides a review of the main features of the rain gauge networks shown in the new global database that include that already found in Morbidelli et al. (2020). It is worth noting that in the following sections the history of selected stations in some representative study areas is described, while specific details of the rain gauges can be found in the Supplementary Material (click here).

3.1. Chaco province (Argentina)

The rain gauge network in the Chaco Province (located in the northern Argentina) started with a single station in 1928 and was expanded in the 1950 s (mainly 1954–1956) with 47 more stations, all situated in the central and eastern parts of the province, while none were in the northwestern part (Hurtado, 2018). Subsequent campaigns to add rain gauge stations focused more on this region, installing three in the 1970 s, two in the 1980 s, and four in 1993. Globally, in the 1970 s, eight additional stations were installed, reaching a total of 56 rain gauge stations (Fig. 6).



R. GENIO CIVILE - SERVIZIO IDROGRAFICO

SEZIONE AUTONOMA DI ROMA

Bacino del

Anno 1936

Pluviometro di Montefalco

Mese di Maggio

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 al suolo	Osservazioni
1	2	3	4	5	6	7	8	9	10
1	9	3/4 c							
2	〃	c							
3	〃	3/4 c				Dalle 10 a notte	6.8		
4	〃	c	nebbia						
5	〃	3/4 c							
6	〃	2/4 c							
7	〃	1/4 c							
8	〃	〃							
9	〃	〃							
10	〃	2/4 c							
						Somma 1ª decade	6.8		
11	9	1/4 c							
12	〃	sereno							
13	〃	3/4 c							
14	〃	〃				Dalle 16 alle 18	3.4		
15	〃	〃							
16	〃	3/4 c				Dalle 17 alle 18	4.2		
17	〃	〃							
18	〃	〃							
19	〃	3/4 c							
20	〃	[illegible]	[illegible]						
						Somma 2ª decade	7.6		
21	9	3/4 c	[illegible]						
22	〃	〃				Dalle 18 a notte	20		
23	〃	〃	〃			Dalle 16 alle 18	10,4		
24	〃	1/4 c							
25	〃	〃							
26	〃	〃							
27	〃	c				Dalle 17 alle 17.30	1.2		
28	〃	3/4 c				Dalle 14 alle 16	51		
29	〃	c							
30	〃	3/4 c				nella notte	11		
31	〃	c				〃 〃	6		
						Somma 3ª decade	99.6		
						Totale del mese	104.-		

L'Osservatore

Fig. 1. Manually recorded daily rainfall data during the month of May 1936 for the Montefalco station (Umbria region – central Italy).

3.2. Neuquén and Limay basins (Argentina)

According to the Argentine National Hydrological Network, there are 14 rain gauges in total within the Neuquén and Limay basins (northern Argentina), although their distribution is uneven: 12 are in the Neuquén basin, while only 2 are in the Limay basin (Fig. 7).

Out of the 14 gauges, 12 are conventional, and 2 are telemetric. They provide daily data ($t_a = 1440$ min), with records generally running from the early 1970 s to about 2019. The most extensive records come from the "Paso de Indios" gauge, which began in 1942.

3.3. Buenos Aires province (Argentina)

The Province of Buenos Aires (Argentina) hosts the Observatory station of La Plata, operated by the Faculty of Astronomical and Geophysical Sciences. Data from these observations started being published on October 1st, 1885, in annual reports that continued without interruption until volume XIV. Additionally, since 1893, this station managed a network of 17 conventional stations across Buenos Aires Province. Since 1896, additional data were taken from 62 rainfall stations (usually located in railway stations) throughout the province. This practice continued until 1902, when, following a major economic crisis in the province, the network was transferred to the National Meteorological Office (now the National Meteorological Service), except for the station located at the Observatory.

In 1996, an additional automatic station began operating alongside the conventional station and since 2014 more automatic stations have been installed in the region. These now form a mesoscale meteorological network, including five stations, that covers much of the La Plata district.

3.4. Austria (whole country)

The Hydrographical Service of Austria is recording rainfall since the

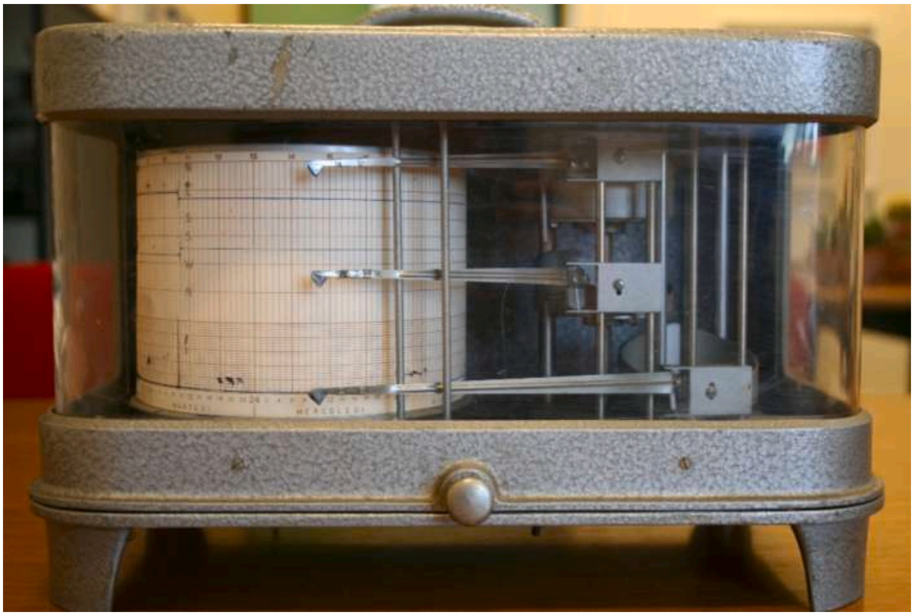


Fig. 2. Rainfall data recorder with paper roll adopted during the 20th century in many geographical areas of the World.

Fig. 3. Rain gauge station with tipping bucket sensor (left) and correspondent digital data-logger (right) installed in central Italy (Compresso, Umbria).

late 19th century. From the beginning until today the most widely used measurement method are daily hand observations with an ombrometer. Registering floater gauges equipped with writing strips first appeared at the break of the 20th century. In the 1950 s they started to become widely adopted and by the 1990 s almost 200 were in use. The writing strips were digitized with varying accuracy and temporal resolution and were therefore assigned a “plausible” temporal resolution of 30 min. Floater gauges were typically taken out of operation during the winter months before the 1980 s. Since the 1980 s floater gauges are being replaced by tipping bucket and predominantly weighing gauges. These gauges record precipitation digitally and the data is often transmitted wirelessly in real-time. Currently, 483 of these gauges are recording with $t_a = 1$ min and 39 gauges are recording with $t_a = 5$ min. At 409 stations, daily hand measurements are still taken in parallel to automatic measurement.

3.5. *Tarija Department (southern Bolivia)*

According to the National Service of Meteorology and Hydrology of Bolivia, the first meteorological stations in the area date back to 1943 and 1944 with the implementation of rain gauges in the main urban settlements and airports within the region and $t_a = 1440$ min. Since that time, 143 rain gauges have been installed in the department, 48 of which are currently active.

In the 70′s the biggest leap in monitoring took place, with the activation of around 50 rainfall monitoring stations. Since the year 2000, due to modernization and automation, there has been significant increases in new weather stations and replacement of old rain gauges (Fig. 8), especially during the period 2005–2018, which increased the frequency of rainfall measurement to 10 or 15 min.

Table 1
Main characteristics of rainfall recordings for the rain gauge stations included in the updated 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]
Albania	3	2/9	2016	2024	1
Algeria (northern region)	30	9/41	1968	2010	1440
Antigua e Barbuda	1	2	2014	2015	1
Argentina (Neu./Lim. basins)	14	34/83	1942	2024	60/1440
Argentina (Prov. Chaco)	64	42/97	1928	2024	770/1440
Argentina (Prov. Córdoba)	69	2/84	1941	2024	5/1440
Argentina (Prov. Buenos Air.)	23	9/140	1885	2024	5/1440
Australia (whole country)	17,768	1/184	1805	2024	1/1440
Austria (whole country)	1,248	1/173	1838	2024	1/1440
Bahamas (whole country)	94	1/24	2000	2024	1440
Bangladesh (whole coun.)	35	19/77	1940	2024	180/1440
Barbados	4	4/9	2012	2024	1
Benin	1	4	2021	2024	1
Bolivia (Tarija)	143	1/81	1943	2024	10/1440
Bolivia	12	3/9	2015	2024	1
Brazil (eastern region)	1	60	1965	2024	1440
Brazil (whole country)	19,802	1/169	1846	2024	10/1440
Burkina Faso	1	4	2021	2024	1
Canada (whole country)	1,977	1/24	2000	2024	1440
Chile (El Rutal)	1	4	2011	2014	5
Chile (central region)	26	23/59	1959	2024	15/60
China (various areas)	7	5/11	2006	2017	10/30
Cyprus (central region)	7	54/144	1881	2024	10/518400
Czechia (Nucice basin)	3	5/13	2012	2024	5
Dominica	6	1/5	2012	2021	1
Estonia (whole country)	51	3/138	1860	2024	10/1440
Ghana	1	4	2021	2024	1
Greece (whole country)	769	1/73	1951	2024	10/360
Grenada	2	7/9	2012	2020	1
Guyana	1	5	2018	2022	1
India (Tapi basin)	54	41/97	1930	2024	1/1440
Italy (Benevento)	2	49/140	1884	2024	10/43200
Italy (Basilicata region)	170	1/74	1920	2024	60/1440
Italy (Calabria region)	119	13/108	1916	2024	1/1440
Italy (Campania region)	352	1/72	1928	2024	10/60
Italy (Lazio region)	330	5/109	1916	2024	1/1440
Italy (Liguria region)	392	2/142	1883	2024	5/1440
Italy (Marche region)	246	1/109	1900	2024	15/1440
Italy (Piedmont region)	324	1/38	1987	2024	1/1440
Italy (Sardinia region)	73	90/103	1921	2024	1/1440
Italy (Sicily region)	18	17/108	1916	2024	5/60
Italy (Tuscany region)	908	1/103	1916	2024	1/1440
Italy (Umbria region)	152	8/103	1915	2024	1/1440
Italy (Valle d'Aosta region)	104	11/158	1841	2024	1/1440
Italy (ACRONET Parad.)	174	2/13	2012	2024	1
Ivory Coast	1	4	2021	2024	1
Malaysia (whole country)	46	6/103	1879	2024	1/1440
Mali	1	1	2021	2021	1
Malta (whole country)	10	12/81	1922	2024	1/1440
Mongolia (western region)	2	49/62	1963	2024	1/720
Morocco (Fez-Meknes region)	83	5/56	1961	2019	1440
Morocco (whole country)	189	11/124	1901	2024	5/1440
Mozambique	5	3	2022	2024	1
Nigeria (whole country)	45	1/7	2016	2024	60
Paraguay	1	5	2019	2023	1
Poland (whole country)	1,576	1/85	1945	2024	1/1440
Poland (Kujaw.-P. region)	10	1/164	1861	2024	5/43200
Poland (Lubelskie region)	11	7/101	1922	2024	5/1440
Romania (whole country)	158	17/140	1885	2024	10/1440
Saint Kitts and Nevis	1	11	2012	2022	1
Saint Lucia	4	4/10	2012	2024	1
Saint Vincent and The Gran.	8	1/9	2012	2024	1
South Korea (Seoul)	1	117	1907	2024	1/480
South Korea (whole country)	2,458	1/121	1904	2024	1/1440
Spain (Andalusia region)	3	35/82	1942	2024	10/1440
Spain (Barcelona)	1	111	1914	2024	1/1440
Spain (Madrid 1)	1	105	1920	2024	10/1440
Spain (Madrid 2)	10	6	2019	2024	1
Spain (San Fernando)	1	189	1805	2024	1/>1440
Spain (Venero Claro-Av.-Ca.)	18	1/87	1931	2024	5/1440
Sudan	1	5	2019	2023	1
Sweden (Uppsala region)	64	1/131	1893	2024	15/1440
The Netherlands	686	1/178	1847	2024	10/1440

(*continued on next page*)

Table 1 (*continued*)

Country (Area)	Rain gauges [number]	Record length min/max [years]	Beginning of records [year]	Ending of records [year]	Time resolution min/max [minutes]
Togo	1	4	2021	2024	1
Tunisia (whole country)	189	7/108	1894	2024	60/43200
USA (whole country)	69,545	1/26	1998	2024	1440
USA (Colorado State)	5,732	1/158	1867	2024	1/1440

3.6. Brazil (whole country)

In Brazil, rainfall measurements are characterized by different time resolutions, mainly associated with the technological advances in time-recording devices. The rainfall monitoring network includes non-automatic gauges (i.e., Ville de Paris rain gauges) with $t_a = 1440$ min and automatic stations (i.e., pluviographs with digital data loggers) with t_a ranging from 10 to 60 min depending on the data source. Fig. 9 shows the evolution of the number of rain gauges over time in Brazil. The earliest available rainfall observation dates back to the early 20th century with non-automatic rain gauges, showing the greatest availability of data in the 1970 s and 1980 s. In contrast, measurements with automatic rain gauges began in 2000 and peaked near 2015. Spatially, the distribution of non-automatic and automatic rain gauges shows high heterogeneity. Overall, non-automatic rainfall data are well distributed throughout Brazil, except for a lower density of rain gauges in the Amazon region. On the other hand, automatic stations are strategically distributed in cities and mountainous areas and are used to warm of natural disasters caused by rainfall events.

3.7. Nucice catchment (Czech Republic)

The climate of the Nucice experimental catchment, located in Central Bohemia, is humid continental with an average annual precipitation of 630 mm (1975–2015 period).

Three rain gauges (tipping bucket sensors with 0.1 mm resolution)

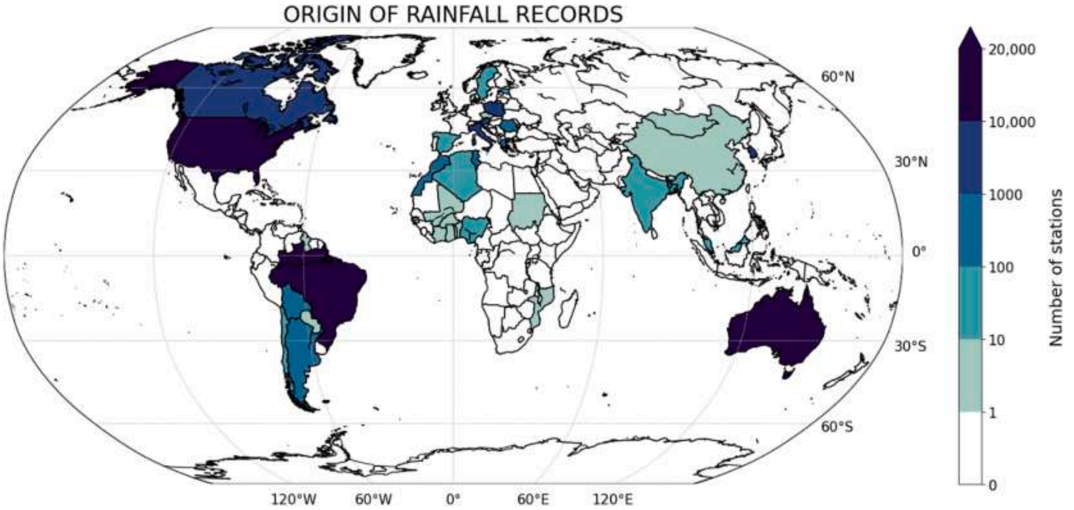
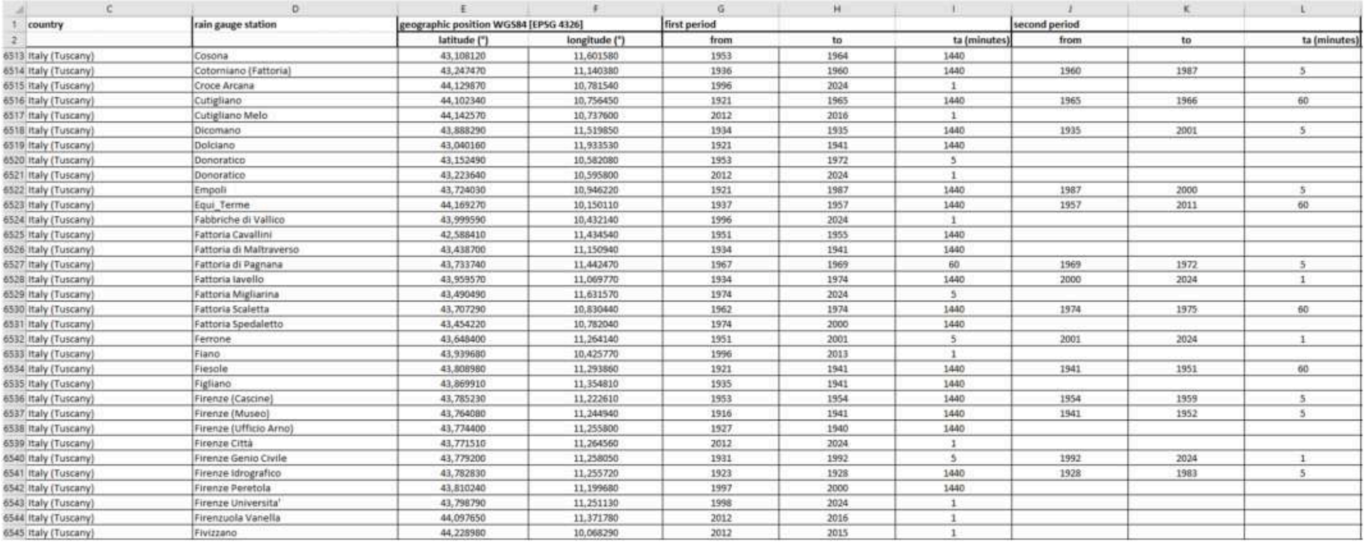


Fig. 4. Number of rain gauges stations available in each country in the updated database.



	C	D	E	F	G	H	I	J	K	L
1	country	rain gauge station	geographic position WGS84 [EPSG 4326]		first period			second period		
2			latitude (°)	longitude (°)	from	to	ta (minutes)	from	to	ta (minutes)
6513	Italy (Tuscany)	Cosona	43,108120	11,601580	1953	1964	1440			
6514	Italy (Tuscany)	Cotorniano (Fattoria)	43,247470	11,140380	1936	1960	1440	1960	1987	5
6515	Italy (Tuscany)	Croce Arcana	44,129870	10,781540	1996	2024	1			
6516	Italy (Tuscany)	Cutigliano	44,102340	10,756450	1921	1965	1440	1965	1966	60
6517	Italy (Tuscany)	Cutigliano Melo	44,142570	10,737600	2012	2016	1			
6518	Italy (Tuscany)	Dicomano	43,888290	11,519850	1934	1935	1440	1935	2001	5
6519	Italy (Tuscany)	Dolciano	43,040160	11,933530	1921	1941	1440			
6520	Italy (Tuscany)	Donoratico	43,152490	10,582080	1953	1972	5			
6521	Italy (Tuscany)	Donoratico	43,223640	10,595800	2012	2024	1			
6522	Italy (Tuscany)	Empoli	43,724030	10,946220	1921	1987	1440	1987	2000	5
6523	Italy (Tuscany)	Equi_Terme	44,169270	10,150110	1937	1957	1440	1957	2011	60
6524	Italy (Tuscany)	Fabbriche di Vallico	43,999590	10,432140	1996	2024	1			
6525	Italy (Tuscany)	Fattoria Cavallini	42,588410	11,434540	1951	1955	1440			
6526	Italy (Tuscany)	Fattoria di Maltraverso	43,438700	11,150940	1934	1941	1440			
6527	Italy (Tuscany)	Fattoria di Pagnana	43,733740	11,442470	1967	1969	60	1969	1972	5
6528	Italy (Tuscany)	Fattoria Iavello	43,959570	11,069770	1934	1974	1440	2000	2024	1
6529	Italy (Tuscany)	Fattoria Migliarina	43,490490	11,631570	1974	2024	5			
6530	Italy (Tuscany)	Fattoria Scaletta	43,707290	10,830440	1962	1974	1440	1974	1975	60
6531	Italy (Tuscany)	Fattoria Spedaletto	43,454220	10,782040	1974	2000	1440			
6532	Italy (Tuscany)	Ferrone	43,648400	11,264140	1951	2001	5	2001	2024	1
6533	Italy (Tuscany)	Fiano	43,939680	10,425770	1996	2013	1			
6534	Italy (Tuscany)	Fiesole	43,808980	11,293860	1921	1941	1440	1941	1951	60
6535	Italy (Tuscany)	Figliano	43,869910	11,354810	1935	1941	1440			
6536	Italy (Tuscany)	Firenze (Cascine)	43,785230	11,222610	1953	1954	1440	1954	1959	5
6537	Italy (Tuscany)	Firenze (Museo)	43,764080	11,244940	1916	1941	1440	1941	1952	5
6538	Italy (Tuscany)	Firenze (Ufficio Arno)	43,774400	11,255800	1927	1940	1440			
6539	Italy (Tuscany)	Firenze Città	43,771510	11,264560	2012	2024	1			
6540	Italy (Tuscany)	Firenze Genio Civile	43,779200	11,258050	1931	1992	5	1992	2024	1
6541	Italy (Tuscany)	Firenze Idrografico	43,782830	11,255720	1923	1928	1440	1928	1983	5
6542	Italy (Tuscany)	Firenze Peretola	43,810240	11,199680	1997	2000	1440			
6543	Italy (Tuscany)	Firenze Universita'	43,798790	11,251130	1998	2024	1			
6544	Italy (Tuscany)	Firenzuola Vanella	44,097650	11,371780	2012	2016	1			
6545	Italy (Tuscany)	Fivizzano	44,228980	10,068290	2012	2015	1			

Fig. 5. Screen shot of a part of the global database containing all the data collected on the time-resolution of rainfall (at this new stage the database consists of 126,438 rows).

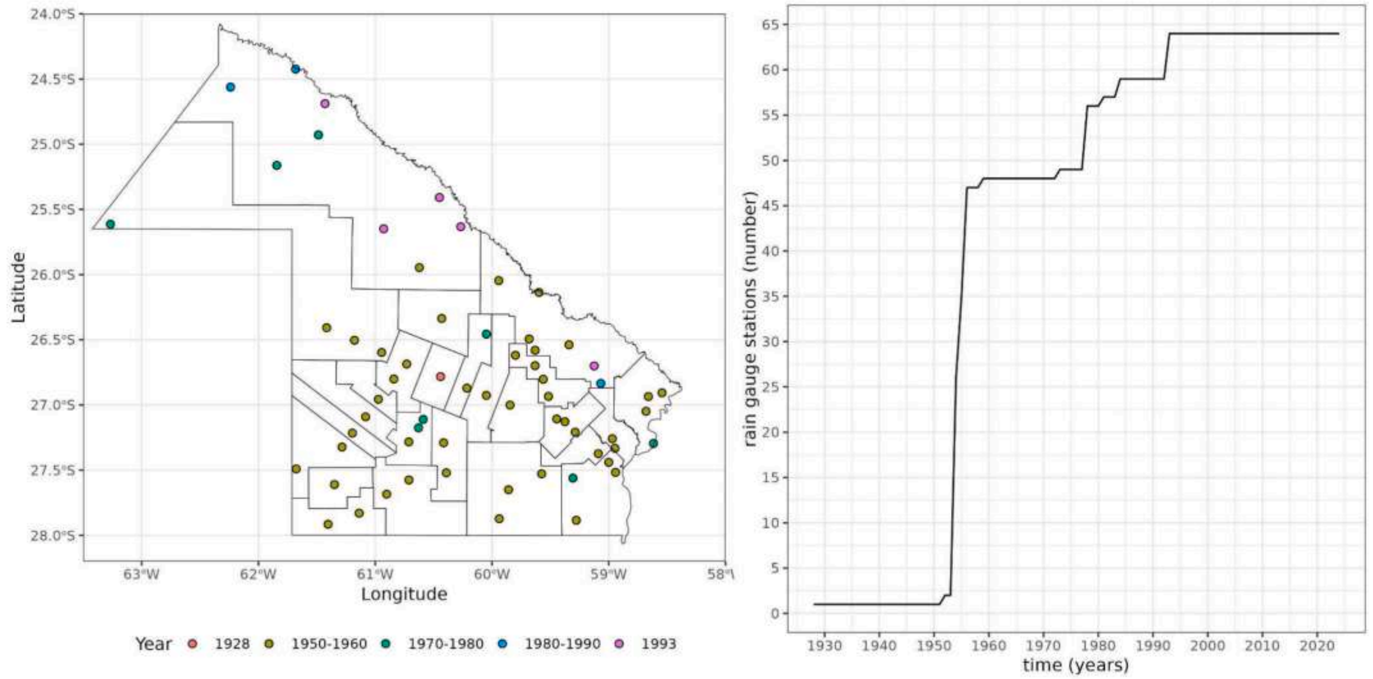


Fig. 6. Rain gauge stations in Chaco Province, Argentina. Left: spatial distribution of rain gauge stations with colors indicating the decade of installation. Polygons represent the departments (political subdivisions) of the province. Right: cumulative number of rain gauge stations over time.

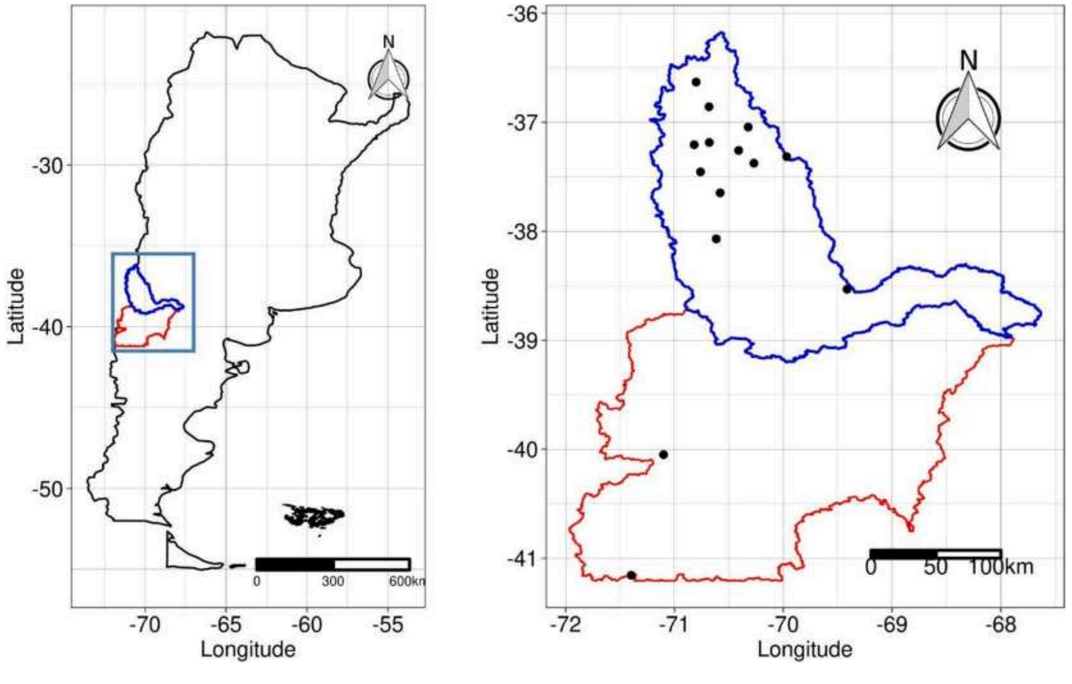


Fig. 7. Neuquen and Limay river's drainage basin in blue and red contours, respectively. Black dots locate the rain gauges within the basins. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are distributed over the 0.5 km^2 catchment area and are about 400 m apart. As can be seen in the Supplementary Material (click here), they were recently installed for research purposes. Rainfall data are recorded with 5-minute time resolution.

3.8. *Greece (whole country)*

The systematic recording of rainfall data in Greece, which can be traced back to the late 19th century, was initially overseen by several governmental and non-governmental authorities.

In recent years, rainfall data collection in Greece has been largely managed by the National Observatory of Athens (NOA) and the Hellenic National Meteorological Service (HNMS). Fig. 10 illustrate the record length of NOA and HNMS stations, showcasing the evolution of their networks over time.

Today, both HNMS and NOA have fully digitized rain-gauge networks, allowing for automated data collection and real-time data transmission to central monitoring systems, supporting both research

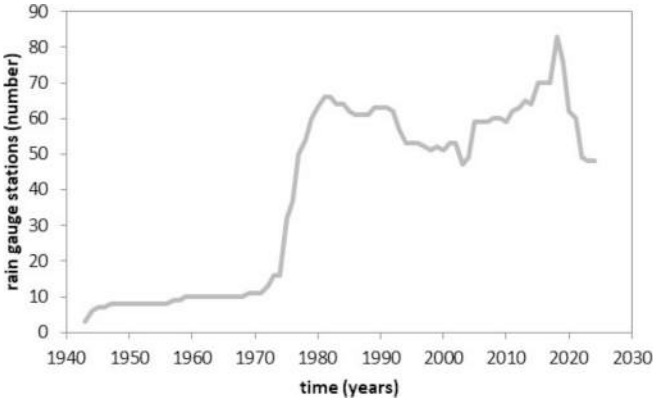


Fig. 8. Rain gauges number evolution with time in Tarija Department, South Bolivia.

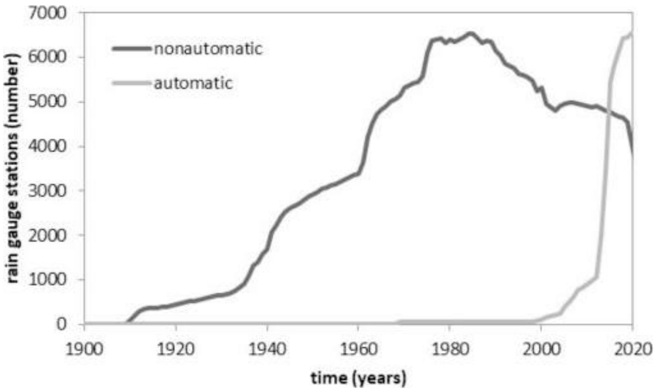


Fig. 9. Numerical evolution over time of automatic and non-automatic rain gauge stations in Brazil.

needs as well as various sectors, including agriculture, construction, leisure, and tourism.

3.9. Basilicata region (southern Italy)

In the Basilicata region (southern Italy), the available rainfall records reported in the new database have been started since 1951 because of the poor spatio-temporal consistency of the data recorded before this period; however, the earlier available rainfall records date back to the first decade of the 20th century in Basilicata.

The National Hydrographic and Mareographic Service (SIMN) managed the initial phase of establishing the network of survey stations and made data available on scanned paper rolls characterized by $t_a = 1440$ min. From 1970, the number of stations declined linearly, with an exception during the 1980 s, when there was an increase in the number of stations (see Fig. 11). Most of the SIMN gauges are now disused, and only a portion of them have been taken over by the Basilicata Region and renewed in technical characteristics and data distribution thanks to the digital transition.

In the 2000 s, in fact, the authorities of the Basilicata Region (i.e., from 2000 to 2010 the Agency for Environmental Protection – Agenzia Regionale per la Protezione Ambientale, ARPA – and from 2010 onward the Decentralized Functional Center – Centro Funzionale Decentralizzato, CFD) carried out a modernization of the network of gauges characterized by $t_a = 60$ min and managed via DataBase. Today, the CFD of Basilicata Region publishes online via WebGIS, for early warning and civil protection purposes, rainfall data in near-real time with sub-hours intervals (all the active stations have a $t_a = 1$ min); however, validated historical data are distributed in digital form aggregated at daily time step ($t_a = 60$ min).

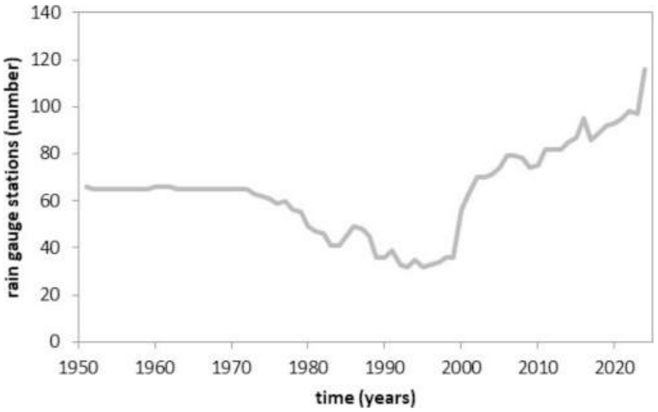


Fig. 11. Rain gauges number evolution with time in Basilicata region, south of Italy.

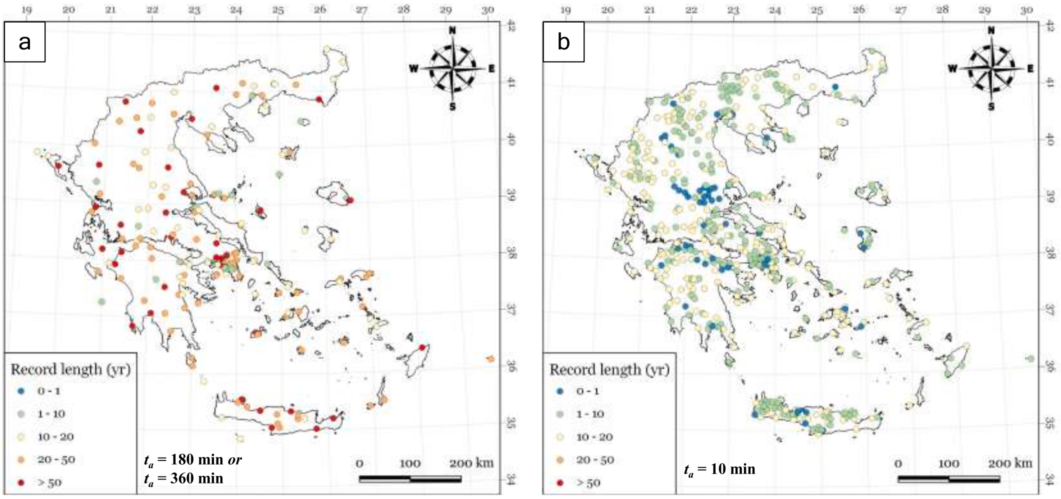


Fig. 10. Spatial distribution of rain gauges operated by a) HNMS (temporal aggregation, t_a , of 180 min and 360 min), and b) NOA (temporal aggregation, t_a , of 10 min). Colors indicate available record length in years.

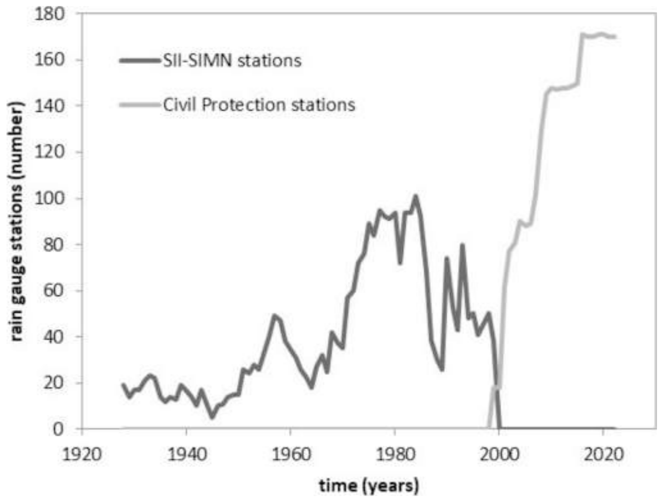


Fig. 12. Rain gauges number evolution with time in the Campania region, southern Italy.

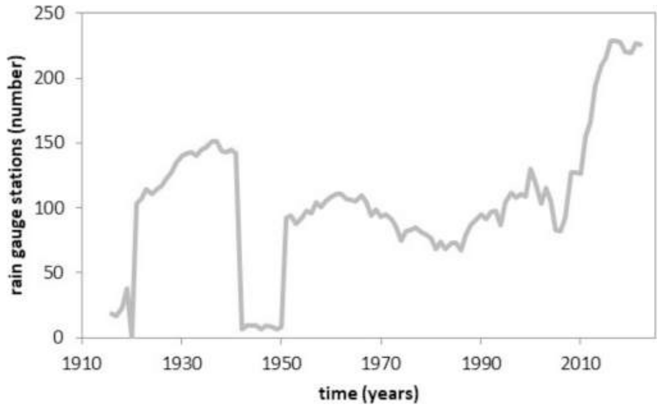


Fig. 13. Rain gauges number evolution with time in Lazio region, central Italy.

3.10. *Campania region (southern Italy)*

In the Campania region (located in southern Italy), the first available rain gauge recordings date back to the second decade of the 20th century (Fig. 12). During these years, the national agency established the monitoring network of the Napoli Compartmental Office starting from a historic core of stations managed by various Entities and Observatories, which, in 1915, consisted of about 80 rain gauges. Over the period 1985–2000, the number of rain-gauge stations decreased because the monitoring duties performed by the national agency were transferred to the regional level. In that period, most rain gauges were removed, relocated or replaced with new-generation instruments to support new civil protection activities. However, this shift has hindered the creation of continuous time series. Indeed, two distinct networks are recognized in Campania: the INHS-SIMN (from 1928 to 1999) network and the Civil Protection network (from 1999 to date).

The first rain-gauge network was managed by national agencies and registered on paper rolls every 5 min. The scanning was manual; thus, operators aggregated data every hour. Therefore, from 1921 to 1999, all the Campania rain gauge stations managed by the national agency were characterized by $t_a = 60$ min. In 1993, the installation of a network of telemetric hydrometric and pluviometric stations began. All the Campania region's rain gauge stations are currently characterized by $t_a = 10$ min.

3.11. *Lazio region (central Italy)*

For the Lazio region (located in central Italy), Fig. 13 shows the number of active rain gauge stations in the 107 years of observation from 1916 to 2022.

In Fig. 13 the active rain gauges are represented regardless of the aggregation time (t_a). From 1916 to 1927 data from both ordinary rain gauges and pluviographs provided rainfall time-series characterized by $t_a = 1440$ min. Starting from 1928, in the Hydrological Yearbooks are available the yearly "maximum intensity precipitation values recorded by the pluviographs" for rainfall durations of 1, 3, 6, 12 and 24 h. Although these rainfall intensities are extracted from continuous time

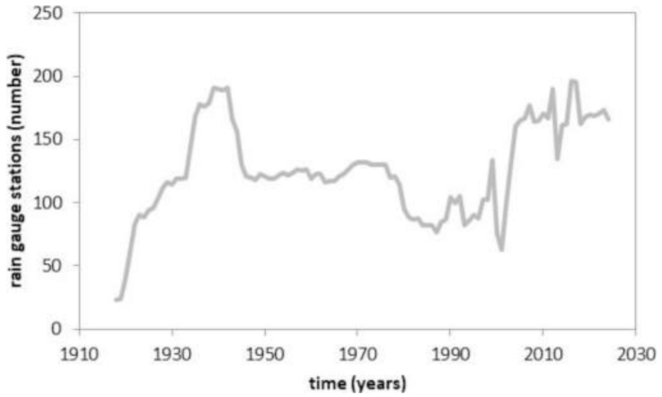


Fig. 15. Rain gauges number evolution with time in the Liguria region, north Italy.

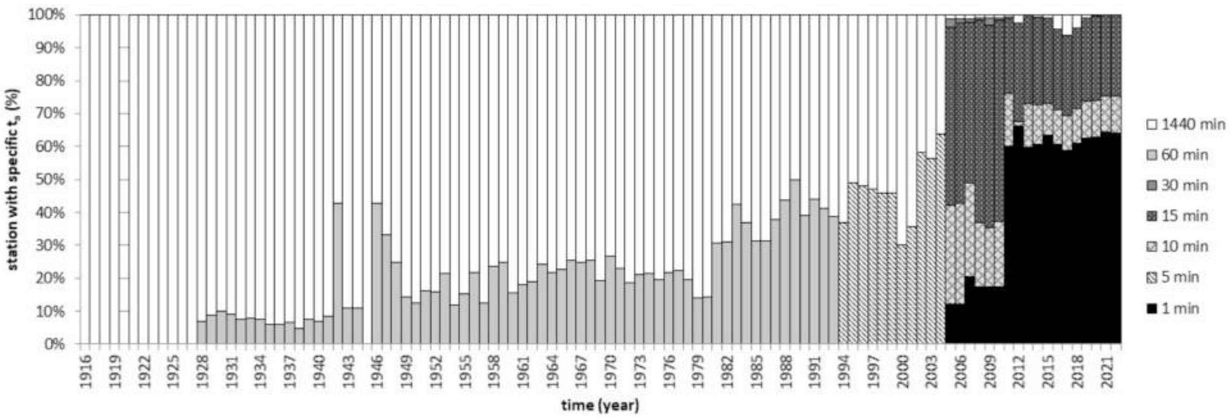


Fig. 14. Percentage of rain gauge stations in Lazio region (central Italy) with specific temporal aggregation, t_a .

series recorded by pluviographs, only starting from 1994 sub-hourly rainfall time series became available at different time scales (e.g., 1, 5, 10, 15 and 30 min). In Fig. 14 the percentage of Lazio rain gauges depending on their temporal aggregations are represented.

It is evident from Fig. 14 that in recent years (since 2011) more than 60 % of the rainfall stations in the Lazio region record rainfall with $t_a =$ 1 min.

Finally, it is noteworthy to highlight that the Collegio Romano station was installed in 1782 by the Ufficio Centrale di Ecologia Agraria (UCEA) resulting as one of the oldest rain gauges station in Italy (Brunetti et al., 2006; Volpi et al., 2024). The Collegio Romano rain gauge is still active nowadays, recording rainfall depths with $t_a = 1$ min.

3.12. *Liguria region (northern Italy)*

In the Liguria region (a coastal area on the Mediterranean Sea in northern Italy with an area of 5,416 km^2) the first available records date back to the fourth decade of the 19th century. In fact, the Meteorological Observatory of the University of Genova, with its rain gauge station has been operating since January 1st, 1833. In June 2021, this station was recognized by the World Meteorological Organization (WMO) as a long-term observing station for more than 100 years of meteorological observations. From January 1st, 1833 to October 16th, 1979, the daily rainfall was measured by dedicated personnel using a storage gauge, then from October 17th, 1979, the storage gauge was replaced by a tipping-bucket rain gauge with registration on paper rolls and its measurements were archived by dedicated personnel at daily resolution until December 31st, 1993. On this date, the instrument was replaced by an automatic tipping bucket rain gauge (equipped with a digital data logger), which archived rainfall measurements at daily resolution until December 31st, 2002, at hourly resolution from January 1st, 2002 to July 28th, 2021, and then at 5-minute resolution to the present day.

The University of Genova (UniGe), at the Department of Civil, Chemical and Environmental Engineering (DICCA), manages a high-resolution rain gauge station (hereafter DICCA-RG). At this station, one-minute resolution measurements are available since 1988 as raw and corrected data, after application of appropriate calibration curves as derived in the laboratory of the WMO Measurement Lead Centre on Precipitation Intensity in accordance with the European standard EN 17277/2019 (CEN, 2019).

Beyond the two rain gauge stations managed by UniGe, the Liguria region counts 395 rain gauge stations in operation between 1918 and 2024, with a maximum of 196 active stations in 2016 (see Fig. 15 for the evolution of the number of rain gauge stations over time), just a few stations (5) more than in 1939.

As can be seen in the Supplementary Material (click here), initially all rain gauge stations in Liguria were characterized by a t_a equal to 1440 min. Since 2001 measurements are available at $t_a = 60$ min except for a few stations for which the data transmission is still at $t_a = 1440$ min. Moreover, with a specific request to be sent directly to the Regional Environmental Protection Agency of Liguria it is possible to obtain data at $t_a = 5$ min for recent years (after 2000).

3.13. *Marche region (central Italy)*

The first rain gauges in the Marche Region (east-central Italy) were installed by the INHS and operated by the Geophysical Observatory of Macerata and were characterized by $t_a = 1440$ min. Since 1919 there was a significant increase in the number of stations installed over the years, peaking in the 1950 s (with approximately 100 stations). The first stations equipped with a digital data logger went into operation in 1990, allowing an increase in temporal aggregation to 15 min for almost all gauges. In the early 2000 s, the transition from national to regional management took place. Since then, specifically from 2002, the stations have been managed by the Regional Functional Center of the Marche Region. Currently (since 2009) all the rain gauge stations in the region are characterized by $t_a = 15$ min (Fig. 16).

3.14. *Piedmont region (northern Italy)*

Rain gauge network installed over Piedmont (northern Italy) is managed by ARPA Piemonte since the dismantlement of the SIMN. The network consists of 323 rain gauges, installed at different elevations, that collect data with $t_a = 1$ min (stored with $t_a = 10$ min). Only one rain gauge (Monviso station) collects data at daily resolution ($t_a = 1440$ min).

The time series cover the period from 1987 up to now. Most of the rain gauges are operative, while 21 of them are no more active.

3.15. *Valle d'Aosta region (northern Italy)*

In the Valle d'Aosta region (an inland area extended 3,262 km^2, elevating up to the top peak of Europe, 4810 m asl), the first available rainfall recordings date back to 1836 at the border with Switzerland, and in 1872 a network of 18 stations was established, but the data are mostly no more available. The network of instruments writing on paper rolls has

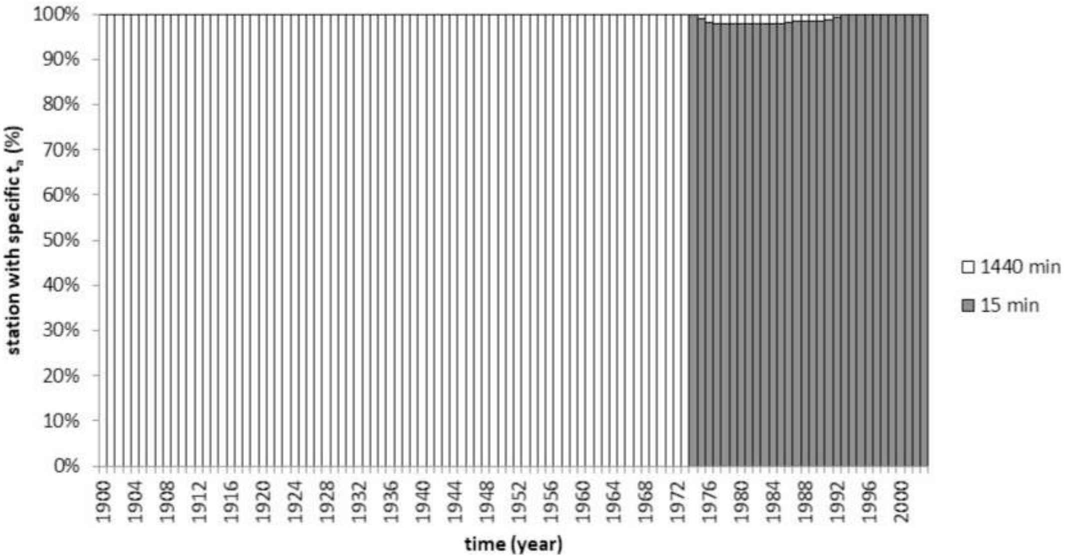


Fig. 16. Number of rain gauge stations in the Marche region (central-eastern Italy) with specific temporal aggregation, t_a .

been installed between 1913 and 1925 by SIMN, and it is now replaced by the automatic network of Centro Funzionale and of ARPA, like in the other Italian region. Nowadays almost 80 rain gauges are operating (12 of them are weighing pluviometers) at elevations ranging between 318 and 2842 m asl, with $t_a = 10$ min.

3.16. Morocco (whole country)

Rainfall measurements in Morocco began in the early 20th century. Initially, “standard” type rain gauges were installed and they collected daily precipitation amounts. Later, in the middle of the century, as the construction of dams and main monitoring stations began, several additional rain gauges were installed. These stations measured precipitation continuously and instantaneously, providing graphic records on graduated paper supports. Analysis of these pluviograms yielded measurements at 15-minute intervals. Finally, at the dawn of the 21st century, some stations were equipped with automatic measuring devices recording quantities at 5-minute intervals.

3.17. Fez-Meknes region (northern Morocco)

The measurement of rainfall in the Fez-Meknes region (northern Morocco) began in colonial times, although data has been lost. After the 1956 the Moroccan kingdom created some important frameworks for watershed management. Rainfall data were collected with a $t_a = 1440$ min by some agencies, namely the Sebou hydraulic basin agency (ABHS), the Oum Er Rabia hydraulic basin agency (ABHOER), and the hydraulic basin agency of the Moulouya (ABHM), in addition to the National Meteorological Directorate (DMN).

3.18. Nigeria (whole country)

Meteorological data observation and collection in Nigeria began in 1892 through an agricultural station under the Public Works Department. Nearly four decades later, in 1937, the country established the Nigerian Meteorological Department (NIMET), which became the primary authority responsible for overseeing all meteorological activities and observations nationwide (Hussaini and Matazu, 2023). While some stations boast data records exceeding a century, the state of the archives varies significantly. The network from which these data archives are obtained, comprises 224 rainfall stations, as well as several agro-meteorological and synoptic stations (Hussaini and Matazu, 2023). However, by 2018, Ngene and Obianigwe (2018) reported that only 87 rain gauge stations were actively operational.

3.19. Poland (whole country)

In Poland, precipitation is systematically recorded by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) through at a total of 1576 meteorological stations. Considering station altitude, there are 966 lowland stations (altitude below 200 m a.s.l.), 457 highland stations (altitude from 201 to 500 m a.s.l.) and 153 mountain stations (altitude above 500 m a.s.l.).

All metadata reported here begin no earlier than 1945/1946 and come from the Database and Archive Department as well as in the Network Management System of the National Hydrological and Meteorological Service of IMGW-PIB.

Since the beginning of the 21st century (although the first attempts began as early as 1999), stations have been equipped with automatic rain gauges (tipping bucket gauges and also weighing gauges), with data recorded in continuous ($t_a = 1$ min). Regarding the frequency of measurements, 661 stations currently measure at a frequency of once every 1 min but publishing resolution is 10 min, according to the IMGW-PIB instructions.

Fig. 17 shows the number of automatic precipitation stations with different temporal resolution during the period 1945–2024. Data prior to 1945 was not included in the study because the Second World War caused disruptions in measurement processes and the data have been preserved only fragmentarily.

3.20. South Korea (whole country)

Rainfall observations in South Korea began in 1904 with three stations under the Central Meteorological Service of the Korean Empire, and the number of stations has steadily increased to a total of about 900. The Korean Meteorological Administration (KMA), is currently

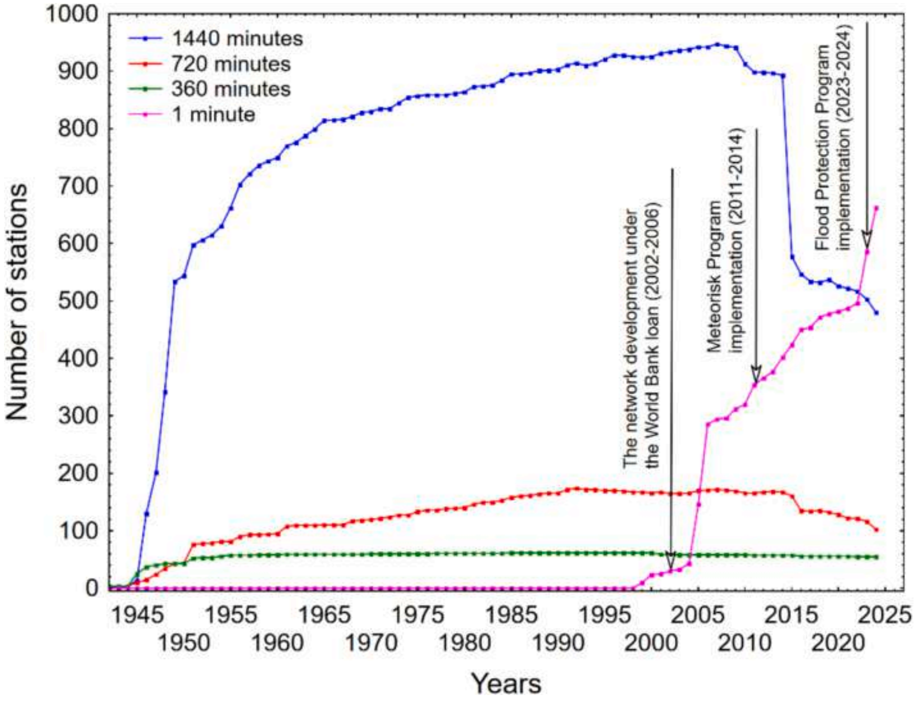


Fig. 17. Number of automatic precipitation stations with different temporal resolutions in Poland during the period 1945–2024.

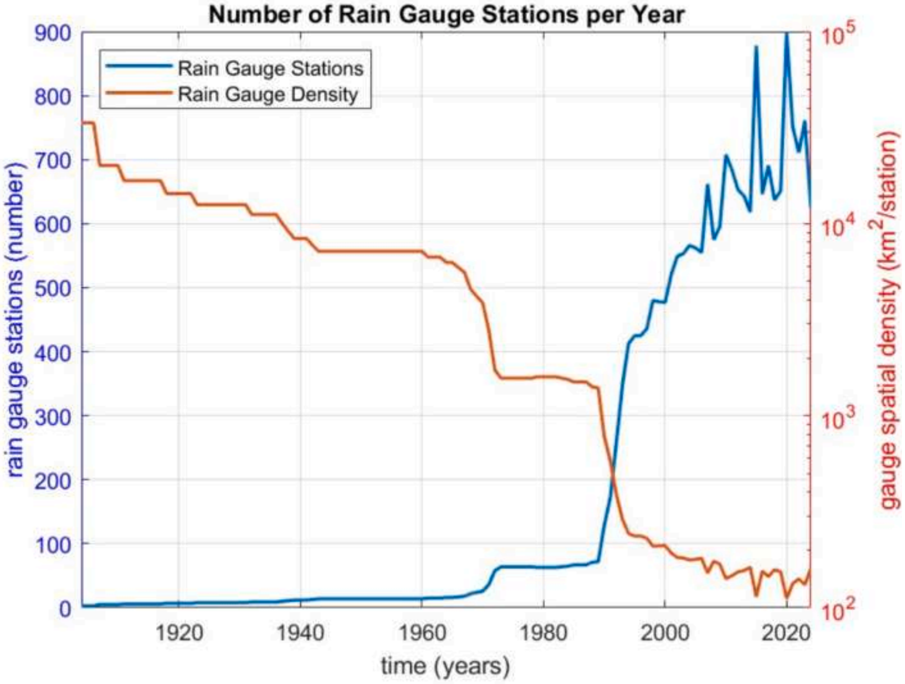


Fig. 18. Temporal evolution of the number of rain gauges in South Korea.

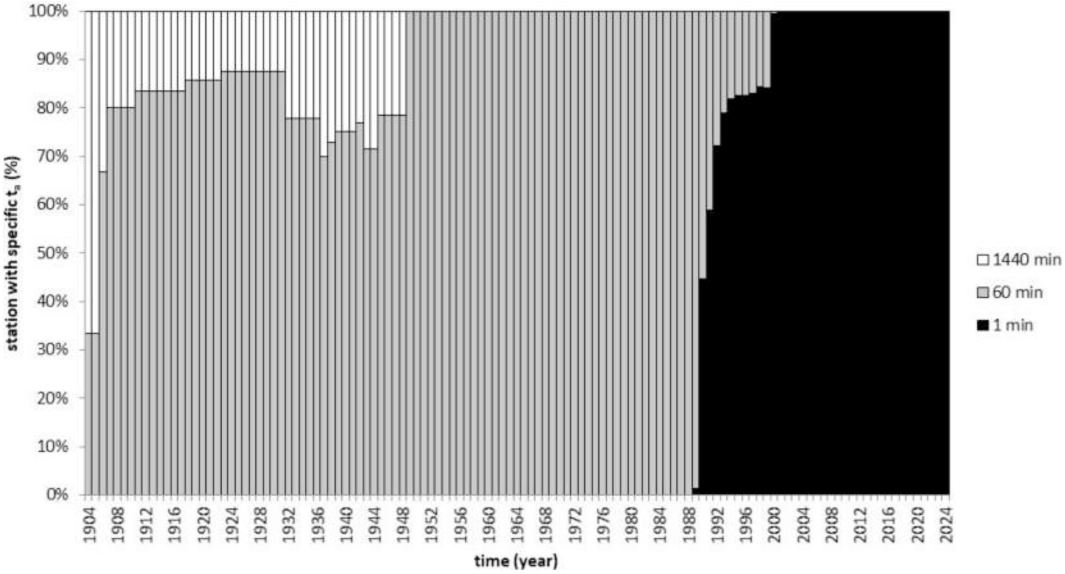


Fig. 19. Percentage of rain gauge stations in South Korea with specific temporal aggregation interval, t_a .

responsible for observing various weather variables, including rainfall. Before 1990, rainfall observations were mainly conducted on an hourly basis through the Automated Synoptic Observing System (ASOS) installed at approximately 90 meteorological offices nationwide. Fig. 18 shows the number of rain gauge stations in South Korea by year. Since 1990, to enhance disaster response, the Automated Weather System (AWS) has been conducting continuous precipitation observations at an additional 500 locations nationwide.

Fig. 19 shows the relative proportion of rainfall observation stations in South Korea classified according to the aggregation intervals of observations. Since the establishment of South Korea in 1948, rainfall observations, which were previously conducted on a mixed daily and hourly basis, were standardized to hourly observations. With the introduction of AWS equipment in 1990, continuous rainfall observations began. Since the early 2000 s, continuous rainfall observations have been conducted at all AWS and ASOS stations.

3.21. *Venero Claro basin (Ávila Spain)*

In the Venero Claro basin (central Spain), hydrometeorological instrumentations consisting of 11 rain gauges of the tipping bucket type with a minimum rainfall measurement frequency of 5 min was installed after an extreme phenomenon (Díez-Herrero, 2001; Segovia-Cardozo et al., 2021a, Segovia-Cardozo et al., 2021b) (). In addition, in the vicinity of this basin a set of 8 rain gauges (with a $t_a = 1440$ min) in the charge of the Spanish State Meteorological Agency dating from 1931 are available (Fig. 20).

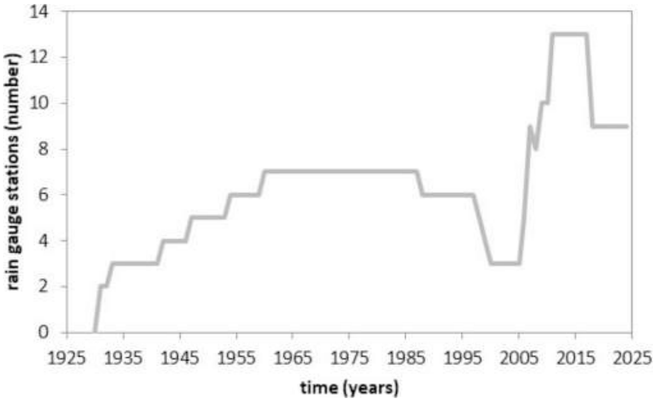


Fig. 20. Rain gauges number evolution in time in Venero Claro, central Spain.

3.22. The Netherlands (whole country)

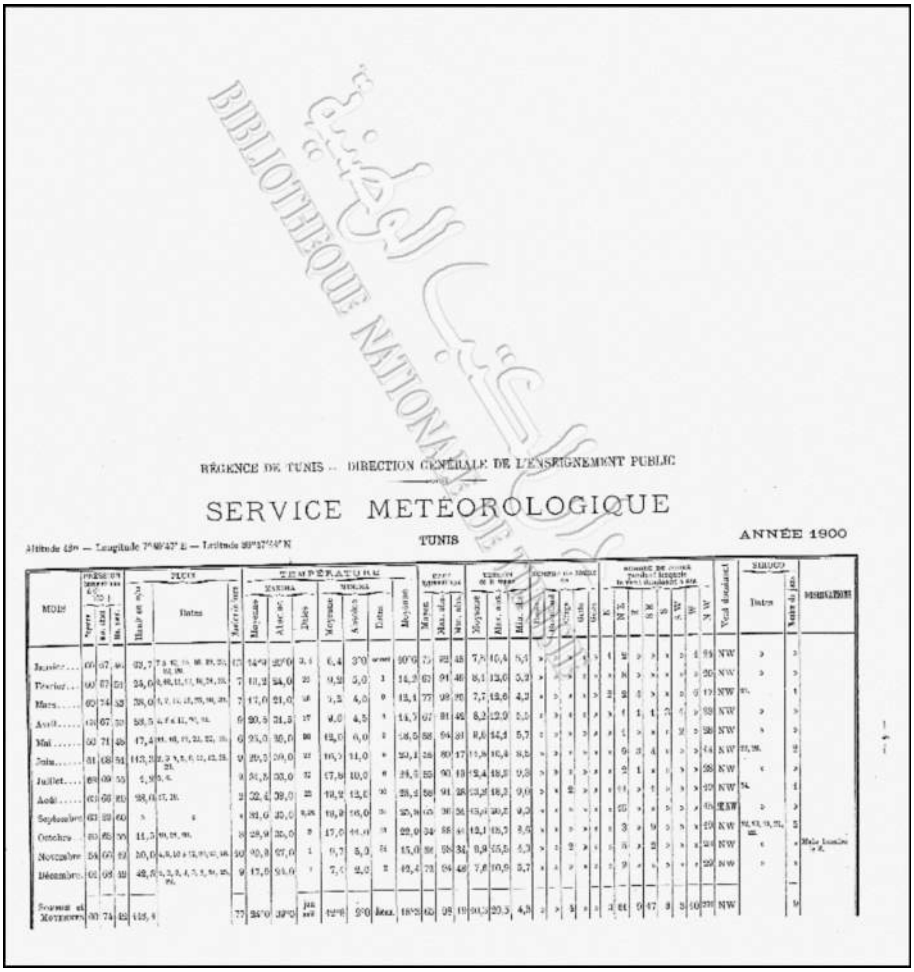
The Royal Netherlands Meteorological Institute (KNMI) operates two precipitation networks: a network of voluntary observers, and a network of automatic rain gauges.

The KNMI manual rain gauge network in the Netherlands is maintained since 1850. There is a gradual increase in the number of rain gauges in the period 1850–1950 and an almost constant network size of about 300 stations since 1951. Currently there are about 320 rain gauges, with an average distance of 9.9 km. The rain gauges are operated by voluntary observers. Each morning the 24 h (0800–0800 UTC) amount of precipitation is measured and since 1995 digitally transferred to KNMI by telephone. Since about 1901 KNMI also measures precipitation automatically. The measurement started using pluviographs as part of so-called climatological stations. Since about 1990 the measurements are made electronically and are part of the KNMI automatic weather stations (AWSs). Today there are 35 AWSs measuring precipitation. Until 2003 the resolution is hourly, thereafter 10-min.

3.23. Tunisia (whole country)

In the annals of meteorological history in Tunisia (Fig. 21), significant milestones mark the evolution of weather observation and the study of climate. It all began in 1873 with the inaugural of meteorological observation. The year 1885 marked a pivotal moment with the establishment of Tunisia’s first meteorological service in Tunis-Manoubia. This pioneering initiative focused on collecting essential data on rainfall patterns and climate variations, setting the stage for systematic observations to come.

Currently, INM (National Institute of Meteorology) has a sophisticated network comprising 26 main stations that records 40 hourly and 64 daily parameters, providing valuable information on Tunisia’s atmospheric dynamics. These main stations are joined by 70 secondary stations, which diligently monitor 16 daily parameters, contributing to a comprehensive understanding of Tunisia’s weather patterns. The INM precipitation measurements are expressed in millimeters and are taken at 6-minute intervals, but are provided on an hourly scale. Together with another network of precipitation stations established since 1875, currently managed by the General Directorate of Water Resources, the



RÉGENCE DE TUNIS – DIRECTION GÉNÉRALE DE L'ENSEIGNEMENT PUBLIC

SERVICE METEOROLOGIQUE

TUNIS

ANNÉE 1900

Fig. 21. An example of a weather report concerning the town on Tunis during the year 1900.

Fig. 22. CoCoRaHS 4-in.-diameter plastic rain gauge-required equipment for each CoCoRaHS observer. The gauge measures to the hundredth of an inch and has an 11.30-in. (287 mm) capacity, with any amount greater than 1 in. flowing into and collecting in the outer cylinder. The funnel and inner cylinder are removed in cold weather for capturing frozen precipitation (Photo by Henry Reges).

total number of stations since that date is 800. However, what is currently operational is a total of 125 stations, which provide daily and even monthly precipitation data.

3.24. *United States of America (whole Country)*

The Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) included in this new database is a precipitation monitoring network composed of thousands of volunteers who manually measure precipitation consistently and report data online (https://www.cocorahs.org). The network, which began as a local community project in response to a local flash flood (Kelsch, 1998), has expanded over time to provide informal weather and climate education opportunities for the public, and it has evolved to provide high-quality daily precipitation data, through the use of simple rain gauges (Fig. 22). CoCoRaHS was first described in the Bulletin of the American Meteorology Society (BAMS) 10 years ago (Cifelli et al., 2005). What was then a small five-state network of volunteer observers has grown to become a leading citizen science example nationwide, with about 27,500 active participants (many of whom take daily surveys), throughout the United States, Puerto Rico, the U.S. Virgin Islands, the Bahamas, and some Canadian provinces. CoCoRaHS (Reges et al., 2016) is now the largest provider of daily manual rainfall measurements in the United States and is one of the largest citizen science networks in the world.

4. Discussion

The update to Morbidelli et al. (2020) reinforced many previously discussed findings during the presentation of the release of the first systematic collection of information on the time resolution of rainfall

Table 2
Year of beginning for manual, mechanical and digital rainfall recordings for each study areas.

Country (Area)	Beginning of manual recording [year]	Beginning of mechanical recording [year]	Beginning of digitized recording [year]
Albania	–	–	2016
Algeria (northern region)	1942	1967	–
Antigua and Barbuda	–	–	2014
Argentina (Neu./Lim. basin)	1942	2019	–
Argentina (Prov. Chaco)	1928	–	1997
Argentina (Prov. Córdoba)	1941	1941	1985
Argentina (Prov Buenos Aires)	1885	–	1996
Australia (whole country)	1826	1920	1989
Austria (whole country)	1838	1895	1979
Bahamas (whole country)	2000	–	–
Bangladesh (whole coun.)	1867	1948	2003
Barbados	–	–	2012
Benin	–	–	2021
Bolivia (Tarija)	1943	1973	2001
Bolivia	–	–	2015
Brazil (eastern region)	–	1965	–
Brazil (northeast region)	–	–	2016
Burkina Faso	–	–	2021
Canada (whole country)	2000	–	–
Chile (El Rutal)	–	–	2011
Chile (central region)	–	1959	2012
China (various areas)	–	–	2006
Cyprus (central region)	1881	1911	2003
Czechia (Nucice basin)	–	–	2012
Dominica	–	–	2012
Estonia (whole country)	1860	–	2009
Ghana	–	–	2021
Greece (whole country)	–	1951	2006
Grenada	–	–	2012
Guyana	–	–	2018
India (Tapi basin)	1925	1969	2012
Italy (Benevento)	1884	1921	2007
Italy (Basilicata region)	1920	1951	2000
Italy (Calabria region)	1916	1916	1989
Italy (Campania region)	–	1928	1993
Italy (Lazio region)	1916	1928	1994
Italy (Liguria region)	1883	1928	1988
Italy (Marche region)	1900	–	1990
Italy (Piedmont region)	–	–	1987
Italy (Sardinia region)	1921	1927	2007
Italy (Sicily region)	1832	1916	2002

(*continued on next page*)

Table 2 (*continued*)

Country (Area)	Beginning of manual recording [year]	Beginning of mechanical recording [year]	Beginning of digitized recording [year]
Italy (Tuscany region)	1916	1928	1991
Italy (Umbria region)	1915	1928	1986
Italy (Val d'Aosta region)	1841	–	1999
Italy (ACRONET Paradigm)	–	–	2012
Ivory Coast	–	–	2021
Malaysia (whole country)	–	1972	–
Mali	–	–	2021
Malta (whole country)	1922	1957	2006
Mongolia (western region)	1963	–	2014
Morocco (Fez-Meknes region)	1961	–	–
Morocco (whole country)	1901	1949	1999
Mozambique	–	–	2022
Nigeria (whole country)	–	–	2016
Paraguay	–	–	2019
Poland (whole country)	1951	1963	2005
Poland (Kujaw.-P. region)	1861	1966	1997
Poland (Lubelskie region)	1922	–	1994
Romania (whole country)	1885	1898	2000
Saint Kitts and Nevis	–	–	2012
Saint Lucia	–	–	2012
Saint Vincent and The Gran.	–	–	2012
South Korea (Seoul)	1907	1915	2000
South Korea (whole country)	1904	1907	1990
Spain (Andalusia region)	1942	–	1980
Spain (Barcelona)	1885	1913	1988
Spain (Madrid 1)	–	1920	1997
Spain (Madrid 2)	–	–	2019
Spain (San Fernando)	1805	–	1987
Spain (Venero Claro-Av.-Ca.)	1931	1954	2006
Sudan	–	–	2019
Sweden (Uppsala region)	1893	–	1986
The Netherlands	1847	1901	2004
Togo	–	–	2021
Tunisia (whole country)	1894	1950	–
USA (whole country)	1998	–	–
USA (Colorado State)	1872	1948	1992

data. In addition, some interesting new features have also emerged.

The database, very important for understanding what kind of analysis is possible in different geographic areas, now contains the t_a-history of 126,438 rainfall stations, located in 77 different study areas (see also the Supplementary Material – click here). Because of the heterogeneity of the sources that were used to obtain the information of the various stations added to the new database, it emerges that the rain gauges belong to networks that insist on spatial scales of sometimes very different extents. Furthermore, although the collected data do not yet cover all countries, they are representative of all continents.

From this reassessment it becomes more clear that the availability of rainfall data has been affected by technological development, which allowed daily data to be acquired until the very first decades of the 19th century, hourly or semi-hourly data in a large intermediate phase of the last century, continuous data in the last 30–35 years (Table 2).

The instruments in operation for over 100 years are very few, always situated in particular locations (f.i. meteorological observatories and religious convents), with rainfall data characterized by coarse temporal aggregations (e.g. $t_a = 1440$ min at La Plata Observatorio in Argentina, from 1885).

The updated database confirmed that great expansion of rain gauge networks occurred after the Second World War, with mechanical recorders allowing aggregation times greater than or equal to 30 min (e.g Tunis Chartage station in Tunisia). The difficulty in keeping stations with digital recording that appeared in recent decades functional is also confirmed, probably due to the high cost of maintenance (see also the temporal evolution of the number of automatic stations in Brazil and Bolivia).

Among the main novelties emerged from the updated database is the implementation of new rainfall networks composed of very inexpensive, hand-reading, volunteer-operated instruments, such as the extensive one in operation in the U.S., Canada, and Bahamas.

In contrast to the past 150 years, when t_a often reduced from 1440 min to 1 min, maintaining a widespread rain gauge network with daily data ($t_a = 1440$ min) enables low-cost monitoring of rainfall across large areas of the world.

An interesting feature is the recent installation of rain gauges by research organizations (e.g., CIMA Research Foundation) in previously unmonitored underdeveloped areas (Barbados, Ivory Coast, Mali, Mozambique, Paraguay, Saint Lucia, …).

The many Italian regions added to this updated database (Basilicata, Campania, Lazio, Liguria, Marche, Piedmont, Valle d'Aosta), along with those included in the database of Morbidelli et al. (2020), showed substantial similarity in the history of the time of aggregation of rainfall data, which takes place over about an entire century. Moreover, similar considerations can also be made regarding various Western European countries (f.i. Austria), while in cases such as Greece, significant development of rainfall networks was reached only in more recent decades.

Many rain gauges located in South America (Brazil, Argentina, Bolivia, …), hardly allow to observe and archive with temporal resolutions lower than 10 min. Regarding the African continent, of particular interest is the possibility of reconstructing the history of the rainfall gauge networks of some northern countries (Morocco, Algeria, Tunisia), while for many of the remainder (Ivory Coast, Ghana, Mali, Mozambique, …) it seems that only recent installations have been carried out by nongovernmental associations.

Finally, it can be seen that South Korea has a particularly efficient rainfall network, with temporal evolution of t_a quite similar to the main countries of Western Europe.

5. Conclusions

The main objective of this paper was to update and expand the database initially created by Morbidelli et al. (2020), documenting the global temporal evolution of rainfall data resolution. While in Morbidelli et al (2020) the database contained the metadata of 25,423 rainfall stations located in 32 study areas, after the expansion made by this work the stations became 126,438, located in 77 different areas.

The importance of such knowledge depends on the fact that over the years rainfall has been observed and recorded using different systems related to the sensors adopted and the corresponding recording system, which have experienced significant changes over the years mainly due to technological development. At the beginning of the last century, time aggregation was very coarse (in some cases, up to 1 month). In recent decades, it has improved significantly, even reaching 1-minute intervals.

The database allows to observe the great heterogeneity of behavior, in terms of t_a, of the different geographical areas of the Earth. In most of the study areas, there has been a shift from manual readings of rainfall thicknesses taken once a day, to mechanical recordings that have enabled hourly or semi-hourly rainfall to be appreciated and recorded, to the use of digital data-loggers, which over the past 30 years have allowed for t_a values of 1 min. This temporal evolution is reflected in the type of analysis that can be conducted, especially relative to the determination of design rainfall or even in analyses aimed at assessing the effects produced by climate change on extreme events.

Maintaining efficient rainfall networks has become a significant problem in recent years, mainly due to high costs; for this reason, too, we are increasingly observing the implementation of rainfall networks made with simple and inexpensive instruments operated by volunteers, characterized by $t_a = 1440$ min. These networks, which are of particular importance for understanding rainfall trends, do not, however, allow detailed study of the characteristics of rainfall of high intensity and short duration.

Although the results of this work are satisfactory, it is acknowledged that more stations could still be integrated into the global database. Therefore, interested readers are urged to contact the corresponding author of this article, communicating information on the aggregation time history of the rainfall stations they manage/know.

CRediT authorship contribution statement

Renato Morbidelli: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alessia Flammini:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Odinakachukwu Echeta:** Writing – review & editing, Data curation. **Raffaele Albano:** Writing – review & editing, Data curation. **Gabriel Anzolin:** Writing – review & editing, Data curation. **David Zumr:** Writing – review & editing, Data curation. **Wafae Badi:** Writing – review & editing, Data curation. **Nicola Berni:** Writing – review & editing, Data curation. **Miriam Bertola:** Writing – review & editing, Data curation. **José María Bodoque:** Writing – review & editing, Data curation. **Theo Brandsma:** Writing – review & editing, Data curation. **Arianna Cauteruccio:** Writing – review & editing, Data curation. **Andrés Cesanelli:** Writing – review & editing, Data curation. **Luigi Cimorelli:** Writing – review & editing, Data curation. **Pedro L.B. Chaffe:** Writing – review & editing, Data curation. **Vinicius B.P. Chagas:** Writing – review & editing, Data curation. **Jacopo Dari:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **Cristiano das Neves Ameida:** Writing – review & editing, Data curation. **Andrés Díez-Herrrero:** Writing – review & editing, Data curation. **Nolan Doesken:** Writing – review & editing, Data curation. **El Mahdi El Khalki:** Writing – review & editing, Data curation. **Mohamed Elmehdi Saidi:** Writing – review & editing, Data curation. **Stefano Ferraris:** Writing – review & editing, Data curation. **Emerson S. Freitas:** Writing – review & editing, Data curation. **Emna Gargouri-Ellouze:** Writing – review & editing, Data curation. **Stefano Luigi Gariano:** Writing – review & editing, Data curation. **Mohamed Hanchane:** Writing – review & editing, Data curation. **Santiago I. Hurtado:** Writing – review & editing, Data curation. **Ridouane Kessabi:** Writing – review & editing, Data curation. **Khaoula Khemiri:** Writing – review & editing, Data curation. **Dongkyun Kim:** Writing – review & editing, Data curation. **Michał K. Kowalewski:** Writing – review & editing, Data curation. **Miina Krabbi:** Writing – review & editing, Data curation. **Marco Lazzeri:** Writing – review & editing, Data curation. **Marco Lompi:** Writing – review & editing, Data curation. **Paola Mazzoglio:** Writing – review & editing, Resources, Investigation, Funding acquisition, Data curation, Conceptualization. **Marcela Antunes Meira:** Writing – review & editing, Data curation. **Benedetta Moccia:** Writing – review & editing, Data curation. **Sara Moutia:** Writing – review & editing, Data curation. **Francesco Napolitano:** Writing – review & editing, Data curation. **Noah Newman:** Writing – review & editing, Data curation. **Lovrenc Pavlin:** Writing – review & editing, Data curation. **Silvia Peruccacci:** Writing – review & editing, Data curation. **Domenico Pianese:** Writing – review & editing, Data curation. **Dina Pirone:** Writing – review & editing, Data curation. **Lorenzo Ricetti:** Writing – review & editing, Data curation. **Elena Ridolfi:** Writing – review & editing, Data curation. **Fabio Russo:** Writing – review & editing, Data curation. **Ruben Horacio Sarochar:** Writing – review & editing, Data curation. **Daniel A. Segovia-Cardozo:** Writing – review & editing, Data curation. **Sergio Segovia-Cardozo:** Writing – review & editing, Data curation. **Athanasios V. Serafeim:** Writing – review & editing, Data curation. **Mariusz Sojka:** Writing – review & editing, Data curation. **Gabriella Speranza:** Writing – review & editing, Data curation. **Grzegorz Urban:** Writing – review & editing, Data curation. **Cosimo Versace:** Writing – review & editing, Data curation. **Andrzej Wałęga:** Writing – review & editing, Data curation. **Sergio Zubelzu:** Writing – review & editing, Data curation. **Carla Saltalippi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2025.132841.

Data availability

Data will be made available on request.

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