UPDATED RAINFALL SERIES AND THEIR TRENDS FOR MAINLAND PORTUGAL (1913–2019)

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ABSTRACT

This paper summarises the main findings from a comprehensive study on rainfall trends based on updated long-running rainfall series from more than 500 stations uniformly dispersed over mainland Portugal (89015 km^2, i.e., almost 60 stations each 10,000 km^2) considering a total period of 106 hydrological years, from October 1913 to September 2019. To understand the rainfall behaviour at different time scales, cumulative intra annual (monthly, quarterly and half-yearly), and annual rainfall series were analysed. To identify possible shifts in the long-term rainfall pattern, two additional contiguous periods were analysed along with the 106-year total period: the initial period, with 55 years and, followed by the final one, with the last 51 years. The detection of the rainfall trends at the different time scales and periods were addressed via the Mann–Kendall (MK) test together with the Sen's slope estimator for measuring the magnitude of the trends. The majority of results achieved revealed that the generalised positive trends in the initial 55 years were followed by negative trends in the last 51 years of the total period clearly outweighing the trends observed in the initial years. This counterbalance resulted in widespread downward trends for the total period. The spatial representation of the magnitude of the trends clearly showed an increasing asymmetry between northern and southern conditions, the latter becoming progressively and remarkable more arid. Such behaviour is also consistent with the previously identified pattern of the "dry gets drier" paradigm for the south western region of the Iberian Peninsula. It was also found that, closely to the year 1968, the intra annual rainfall pattern changed. Since about that year, the rainfall in the last wet months of the hydrological year (January, February, and March) has showed a sustained decrease of its relative weight, thus diminishing its relative contribution to the groundwater refill and to the water needs during the forthcoming dry months.

Keywords: climate change, mainland Portugal, rainfall trends, Mann–Kendall test, Sen's slope test

1 INTRODUCTION

Through the regular scientific assessments on climate change of the Intergovernmental Panel on Climate Change [1], it is pointed out that changes are occurring in the amount, intensity, frequency and type of precipitation. According to these assessments, specifically for rainfall, trends would be positive in some parts of the globe [2]. However, at smaller scales an opposite pattern have been identified with sustained decreasing rainfalls [3]. Despite these patterns are still uncertain, there is enough evidence to still considering them as very likely scenarios as, for instance, for the Iberian Peninsula. According to the reports by [4]–[7] all over the 21st century the Iberian rainfall is likely to decrease at longer time scales, and be grouped in more intense extreme events.

In the case of the Mediterranean region, several studies have addressed climate variables' trends (such as precipitation, specifically its liquid state, i.e., rainfall) based on ground-based measurements during the 20th century, but yet a small number of studies ascertaining the current and future conditions [8]–[10]. This fact highlights that such trend analyses need to be continuously updated since they describe current trends to predict future ones and that almost all the climate variables come from a complex system with changes that may or may not be identified subject to the length and time window of the utilised series. Under such understanding and having in mind the major role of the rainfall in the hydrological cycle, long-term and recent rainfall trends, including their variability and uncertainty over time,

WIT Transactions on Ecology and the Environment, Vol 250,
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/WRM210011

were analysed for mainland Portugal at different time scales, from month to year, by means of the Mann–Kendall (MK) test together with the Sen's slope estimator. The results achieved clearly indicate largely predominant negative MK values, i.e., decreasing rainfalls.

2 CASE STUDY: RAINFALL DATA

The study area is mainland Portugal, with approximately 89,015 km^2, located on the Iberian Peninsula, in the south westernmost part of Europe (centred at latitude 39°23′59.5″N and longitude 8°13′28″W). Portugal faces the North Atlantic Ocean (Fig. 1), and is characterised by a Mediterranean climate with warm and dry summers and cool and wet winters. The major natural factors that substantially determine the Portuguese climate are the latitude, the sharp hilly terrain, ranging from 0 m.a.m.s.l. at the Atlantic Ocean to 1993 m.a.m.s.l. in the Serra da Estrela, and also the weak ocean current that flows south along the coast of the country. The average annual rainfall is in close connection to the relief following a predominantly complex north to south pattern, and thus, varying considerably throughout the country ranging from values above 2,800 mm to less than 400 mm, as shown in Fig. 1.

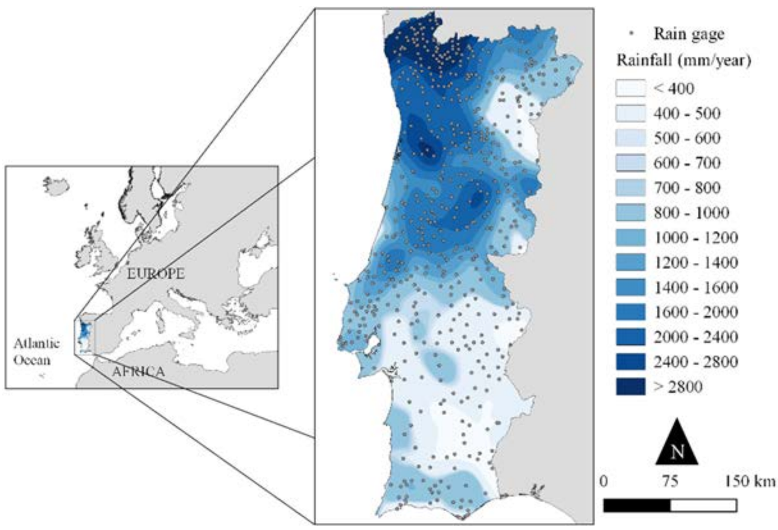

Figure 1: Average annual rainfall of mainland Portugal during the total 106-year period (from 1913/1914 to 2018/2019), and location of the 532 rain gauges analysed in the study.

The monthly rainfall records used in the study were acquired from the public database of the Portuguese Environment Agency [11]. Because most of the rain gauges had missing data, the fill-in procedure described in [12] was applied to the original monthly records, resulting in 532 rain gauges (Fig. 1) with updated long-running monthly rainfall data accounting for 106 hydrological years, each starting October 1 (from October 1913 to September 2019).

3 MODELS

The Mann–Kendall test was used to detect consistent upward and downward trends (i.e., monotonic trends) in the monthly and aggregated rainfall time series [13], [14] for the 95%

confidence interval. Additionally, the Sen’s slope estimator [15] was utilised to determine the magnitude of the trends.

4 RESULTS

The trends at the selected 532 rain gauges were characterised at the annual level but also at the following shorter time scales aiming at ascertaining the within-the-year changes in the rainfall pattern [10], [12]: months, quarters (Q1 to Q4 starting in October, January, April and July, respectively) and semesters (S1, from October to March, and S2, from April to September).

Also, to examine the spatiotemporal dynamics of rainfall in the context of changing climate, the total period of 106 years (from October 1913 to September 2019) was divided into two contiguous periods, i.e., the initial 55 hydrological years (1913/1914 to 1967/1968) and the last 51 hydrological years (1968/1969 to 2018/2019). This was done based on the identified accelerated downward rainfall trends since late 1960s for southern Portugal [10].

The rainfall trend magnitudes obtained from the models were mapped including both statistically significant and non-significant trends (Figs 2–4). The figures considered the three periods, thus, enabling to assess the rainfall changes over time.

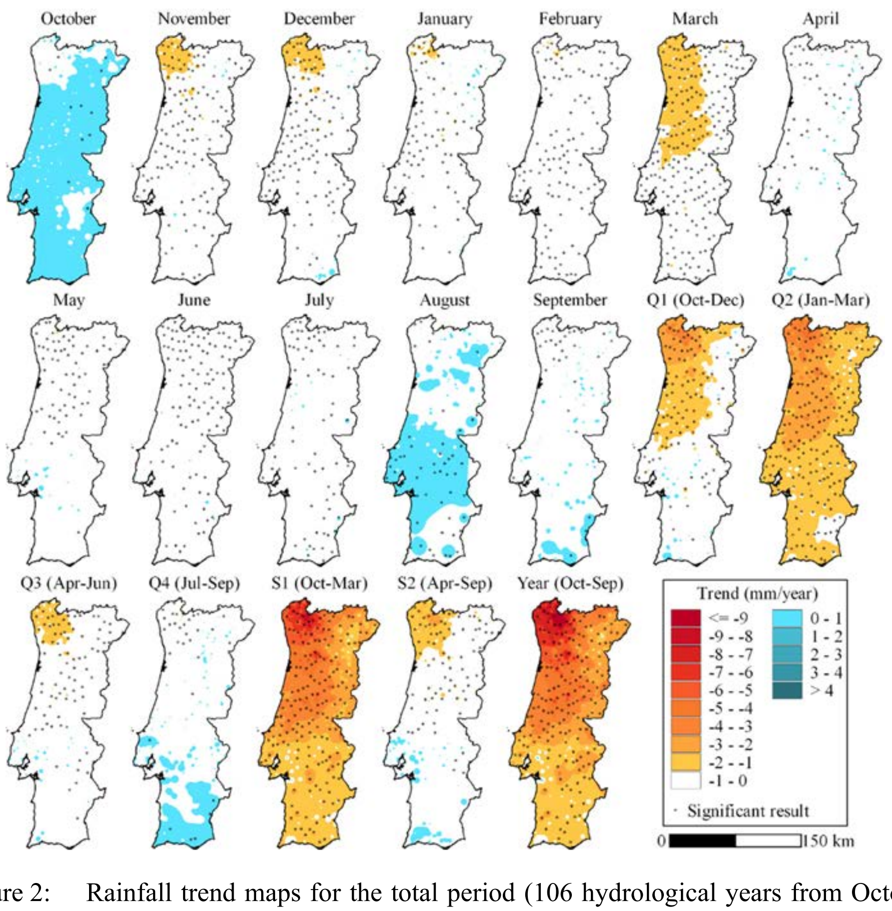

Figure 2: Rainfall trend maps for the total period (106 hydrological years from October 1913 to September 2019) at monthly, quarterly (Q1–Q4), semi-annual (S1 and S2), and annual time scales. *(Source: Adapted from [12].)*

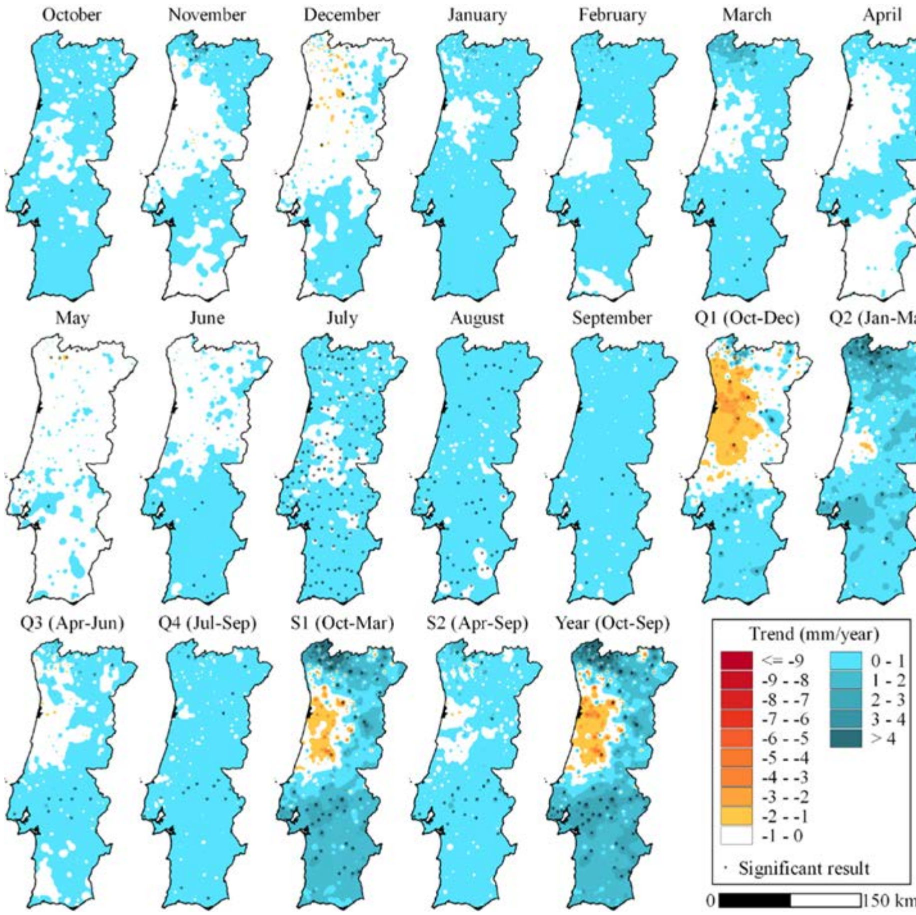

Figure 3: Rainfall trend maps for the initial period (55 hydrological years from October 1913 to September 1968) at monthly, quarterly (Q1–Q4), semi-annual (S1 and S2), and annual time scales. *(Source: Adapted from [12].)*

For the total period, the trend analysis showed generalised decreases in rainfall for longer time scales (e.g., Q2, S1, and the year in Fig. 2). However, these magnitudes were determined from a linear model. Therefore, an improved interpretation was done for the division of the 106 years. During the first 55 years (Fig. 3) large parts of Portugal denoted upward trends. In the following 51 years (Fig. 4), these patterns swung into markedly downward trends except July and August which, either way, provide negligible amounts of rainfall. Hence, the latter period counterbalanced the trends observed in the initial years and resulted in widespread, but less marked, downward trends for the total period.

The comparison on the trend maps of Figs 3 and 4 denoted a relatively rapid "step" change from the initial upward trends to the final downward trends, respectively. This contrast is highly marked for Q1, Q2, S1, and the year with more steep declines in the earlier years. The comparison now including Fig. 2 reveals some relevant rainfall distribution changes at monthly scale. For instance, March is the month with the highest number of significant and most pronounced trends for the total period. Nevertheless, by inspecting Fig. 4, apparently the most significant changes take place in the two previous months. This suggests that the notorious monthly rainfall decline is shifting "backwards" from March to February and January – note that these months have a determining effect on the groundwater and artificial reservoirs refill and in the water budgets in mainland Portugal.

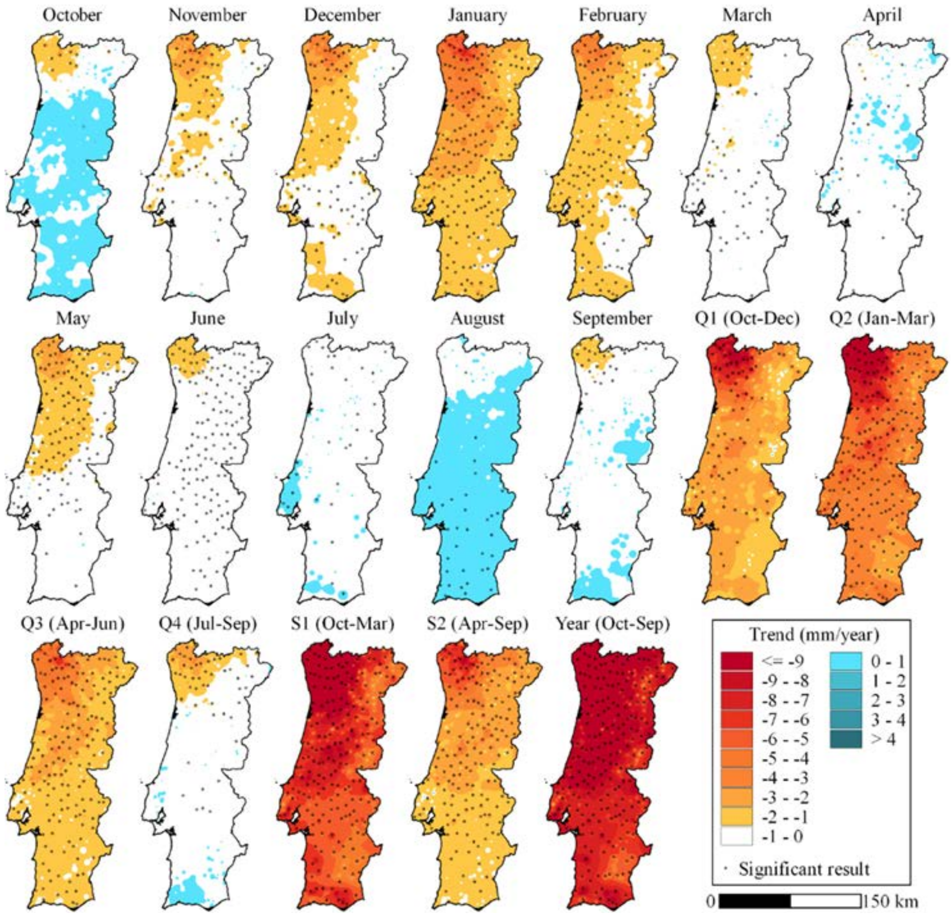

Figure 4: Rainfall trend maps for the last period (51 hydrological years from October 1968 to September 2019) at monthly, quarterly (Q1–Q4), semi-annually (S1 and S2), and annually time scales. *(Source: Adapted from [12].)*

Furthermore, a homogeneous spatial distribution of downward rainfall trends was recognised at seasonal scale over the country, especially in the wet season of the hydrological year (S1, from October to March). This is of great importance given S1 may represent three-quarters or even more of the annual rainfall. However, October denoted only few areas with negative trends compared to the rest of the rainy months (as shown in Fig. 4). This highlights a greater vulnerability to such negative pattern since, based on these results, wetter conditions which could turn round the already dry conditions are not expected to occur.

Analogously, long-term averages at annual level were calculated over the three adopted periods using aggregates of the updated and filled-in rainfall series [12]. The average annual rainfalls are mapped in Fig. 5 including a weighted mean annual value in each case. From the figure, wetter conditions can be observed in the initial 55 years which contrast with the drier ones in the last 51 years given the general rainfall decreases from one period to the other. Such decrease is about 170 mm, also reflecting a more pronounced asymmetric with a relatively still wet north and a conclusively drier south.

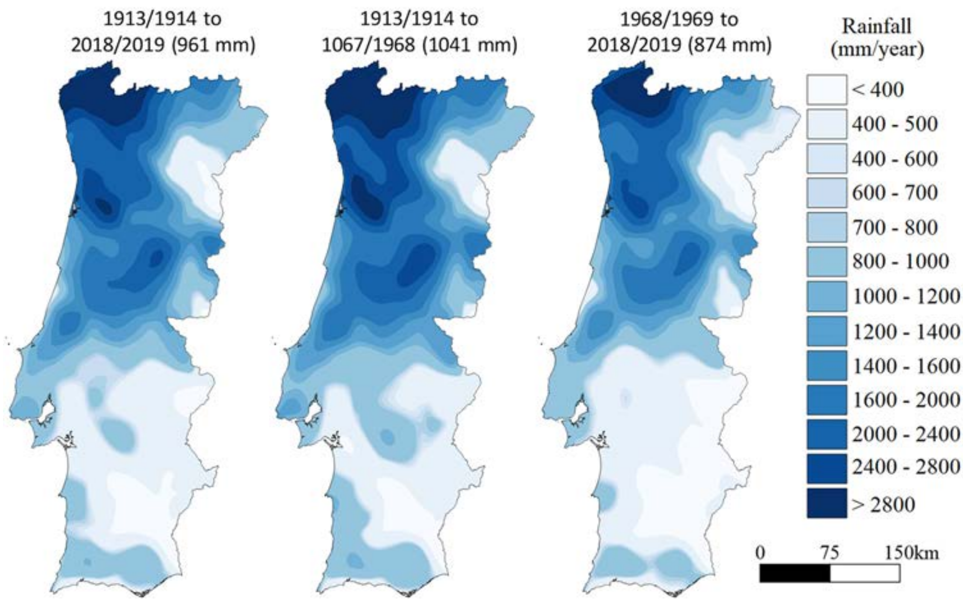

Figure 5: Average annual rainfall maps over the period from 1913/1914 to 2018/2019, and over the initial 55 and last 51 years. The respective weighted annual average is between brackets scales. *(Source: Adapted from [12].)*

In conjunction with the rainfall trend estimates, long-term rainfall anomalies were also calculated to provide a clearer indication of the vulnerability of Portugal to the declining rainfall. The variability of rainfall, i.e., anomalies, were defined, for each of the 532 stations, as the difference between averages of annual rainfall in the last years and in the initial years. The interpolated anomalies both in absolute and relative terms are depicted in Fig. 6 left and right side, respectively. The dimensionless anomalies were obtained by dividing the absolute values by their respective annual average in the initial 55-year.

As seen in Fig. 6 left side, some regions of the country denoted a substantial decrease of more than 500 mm in the average annual rainfall from the initial 55-year period to the last period. Fig. 6 right side on the other hand, evidences a more homogenous rainfall reduction in relative terms affecting the wet (northern) and dry (southern) regions. This suggests that the already dry south is getting even drier. When coupling these patterns with those already described for the rainfall trend and with the average annual rainfall maps, the difference between a drier northern Portugal (but still wet) and a certainly drier arid south is reinforced. This coincides with the claims of [16] who, based on a trend analysis of various hydrological data sets for the reference period from 1948 to 2005, pinpointed the southwest of the Iberian Peninsula as one hot spot of the "dry regions dry out further" pattern, i.e., of the DD paradigm.

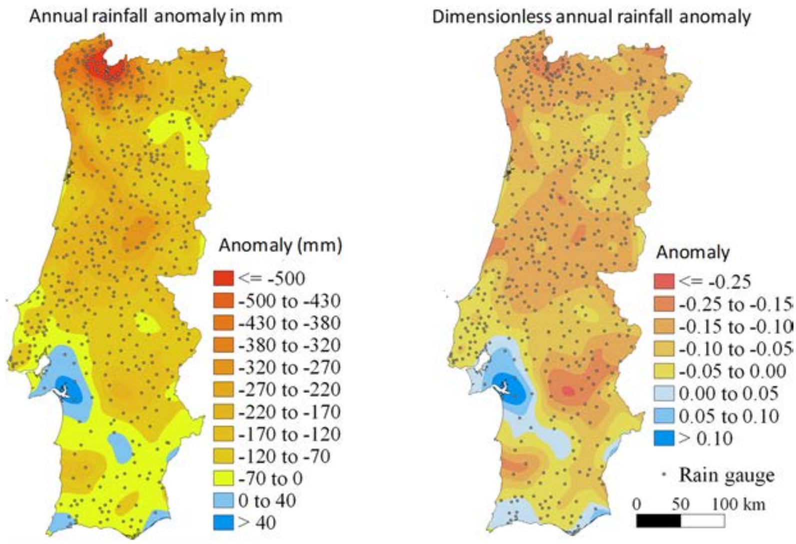

Figure 6: Differences between average annual rainfalls in the last 51-year period (from 1968/1696 to 2018/2019) minus the initial 55-year period (from 1913/1914 to 1967/1968) expressed in absolute terms (left side). The previous differences made relative to their respective average annual rainfalls in the 55-year initial period (right side).

Aiming at understanding the long-term within-the-year modification and uncertainty of the detected rainfall trends for the second trimester of quarter of the hydrological year, a sequential trend analysis was performed for the total period based on rainfall moving averages of the related months of Q2, from January to March. A period of 30 years was adopted as moving time window ($n = 30$ years). For comparison purposes, the rainfall values in each month at the 532 stations were made dimensionless regarding the weighted average annual rainfall of 961 mm (from 1913/1914 to 2018/2019 in Fig. 5).

Each monthly value was assigned to the year in the middle of the 30-year time window. For instance, the first moving average considered the years from 1913/1914 to 1942/1943 and was assign to 1928/1929. In each rain gauge and month, the application of this technique resulted in 77 moving averages for the 106-year period (with 532 values each), being the last moving average, from 1989/1990 to 2018/2019, assigned to 2004/2005. This allowed examining fluctuations of rainfall trend [17] by adopting a commonly used technique for smoothing out climate data series. Time windows of 30 years are also adopted in the computation of the climatological standard normals aiming at to ascertain the climatic conditions likely to be experienced in a given location [18], [19].

For each month of Q2, Fig. 7 shows some of the results from the moving average technique, related to the medians and empirical quantiles (Q) for non-exceedance probabilities between 5% and 95% (Q5% and Q95%, respectively) for the set of 532 rainfall series. For March the three curves thus obtained denoted an upward trend from the start of the total period with turning point in trend around late 1950s, reaching very low values regarding the long-term average. This dynamical pattern apparently “stabilised” from 1970 on with no upward or downward trend. This stabilised pattern was not detected for February nor January which could mean that the rainfall is still going through a somewhat active process of rainfall decrease. The figure also illustrates that the range between the quantiles Q5% and Q95% is getting narrower meaning less rainfall variability among the set of series from the 532 rain gauges, therefore, less uncertainty regarding the detected trends, particularly of the downward trends over mainland Portugal in earlier years.

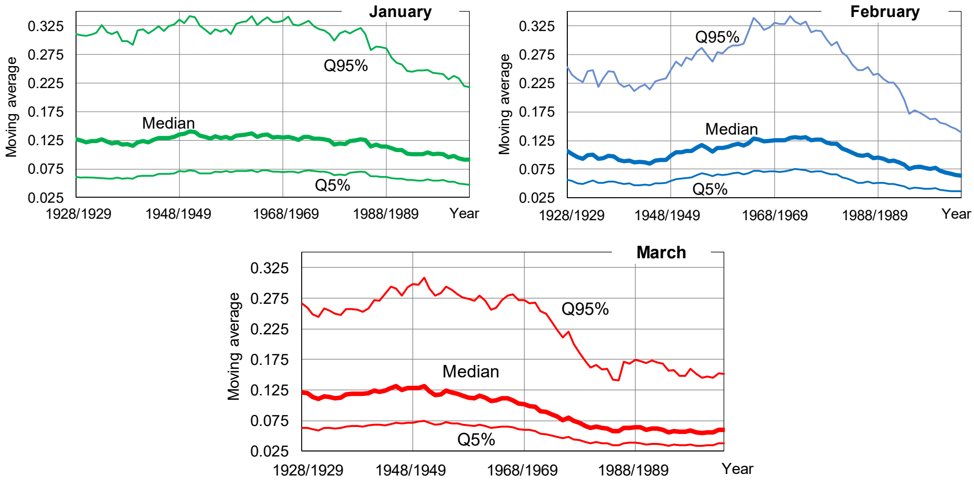

Figure 7: Moving average results, based on monthly rainfalls from the 532 rain gauges, characterised by the median and empirical quantiles for the non-exceedance probabilities of 5% (Q5%) and 95% (Q95%) in relative terms. *(Source: Adapted from [12].)*

5 FINAL REMARKS

Mainland Portugal, as for other regions in the globe, is susceptible to rainfall variability and change. Fluctuations in rainfall is a recurring phenomenon in the study area which has had a more negatively sustained and statistically significant behaviour in recent years as addressed in this work based on densely, updated and long-running rainfall series from 532 rain gauges (from 1968/1696 to 2018/2019 and two subperiods). Therefore, understanding past rainfall variations and updating rainfall trends at relevant time scales play a critical role in water resources management addressing, among different water-related challenges, the water security in the country in a well-recognised changing climate.

Although obtaining a single rainfall pattern for Portugal was not possible – due to the country's complex physical features and different climatic drivers involved in the rainfall process – the results showed strong evidence about the generalised, less uncertain, and widespread rainfall decrease in the country from early 1970 on. This negative trend in rainfall has been affecting the months that contribute the most to the annual rainfall (e.g., January and February), thus strongly determining the within-the-year rainfall pattern. These findings are backed, for instance, by the global evidence of a near future with lower freshwater availability in subtropical latitudes. Overall, this stresses the urge of establishing updated rainfall records to evaluate the change of rainfall and to provide useful information for future rainfall assessments. Furthermore, public participation is a key factor, since this practice calls for updated information and political commitment towards the implementation of mitigation and adaptation measures and of new water resources planning and management policies in the face of current and future severe climate change patterns. Both information and political issues have not yet been fully addressed for mainland Portugal [20].

ACKNOWLEDGEMENTS
For the first and third authors, this work is supported by the FCT – Scientific Cooperation Agreement between Portugal and Slovakia 2019/2020, SK-PT-18-0008, and for the second author by the FCT – grant number PD/BD/128509/2017.

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