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Towards sustainable precipitation management in Madurai Town Planning Area (India)

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Abstract

This study aimed to look for efficient development strategies towards achieving sustainable precipitation management in the Madurai Town Planning Area (MTPA) in India. In the MTPA, precipitation is the predominant source of freshwater for agricultural and domestic uses in addition to water received through conventional systems. The average annual precipitation in the region is ~816 mm with standard deviation of 233 mm. The regression analysis showed that annual precipitation is following a decreasing trend and will be about 716 mm by 2030. The Precipitation Concentration Index (PCI) values ranging from 18 to 20 represented strong irregularities and seasonality in annual precipitation over the study area. March, July, September, and November months contributed 2.5, 6.19, 14, and 16% to annual precipitation, respectively, and all showed decreasing trends over time. Only 20% of Northeast monsoon was active over the past 44 years (1976–2019), resulting in a 15% probability of flood and drought occurrences throughout the MTPA. The long-term (1976–2019) average value of annual precipitation days was about 42. The Concentration Index (CI) showed that 60–70% of precipitation was received within 25% of precipitable days. Daily precipitation class of moderate (7.5–34 mm) and rather heavy (34–64 mm) ranges were the dominant types of precipitation, contributing 46% and 26% to total annual precipitation, respectively. Except for October, the monthly precipitation received was deficit to meet the irrigation water demand in the MTPA. However, development of precipitation harvesting systems can annually preserve about 27 Mm^3 freshwater in the urban space of the MTPA.

Keywords Concentration index · MTPA · Precipitation · Sustainable development · Water security

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1 Introduction

Global warming due to the considerable increases in the anthropogenic concentrations of greenhouses gas emissions into the atmosphere is gaining higher attention around the world every day [1]. The impacts of such warming on the Earth's climate and environment are today the most critical challenges faced by humanity [2]. The global climate and environmental changes are troublesome and evident from the past, with the annihilation of many species, immigration of inhabitants, and noticeable changes in the terrestrial ecosystem and ocean current [3–5]. The haste of the existing worldwide climate and environmental change patterns is much wild than most of the previous events, making it more difficult for nature and civilization to adjust [6]. This highlights climate and environmental changes as one of the most extensively explored subjects during the twenty-first century [7]. Experts, officials, policy-makers, and managers are on the hunt to know the type of sustainability risks they need to mitigate or adapt in near future under such indisputable climate and environmental changes in different parts of the world [8].

In general, global warming induces more erratic weather and climate around the world [9], with substantial alterations in precipitation variability, flood and drought severity, wind velocity and direction, hot spell durations, aridity types, sea level fluctuations, and tidal movements [2, 10, 11]; Warmer air [12] and sea surface [13] temperatures principally increase atmospheric moisture content [14], leading particularly to significant changes in different hydrological cycle components, particularly evapotranspiration and precipitation [15]. As the factors controlling water resources availability, hence, analysing spatio-temporal variations and trends in such components has already been one of the focal research points in climatic and environmental studies [16, 17].

Precipitation basically links atmospheric (e.g., cloud) and land-surface (e.g., soil moisture) hydrological processes [18]. It is commonly considered a key hydrometeorological variable for detecting regional climate change on our planet [19, 20]. On a global scale, there is no conclusive changes in historical mean precipitation [21], while the intensity and frequency of extreme precipitation events increased in recent decades [22]. However, such findings are not essentially translated to similar changes in mean and extreme precipitation characteristics (in terms of intensity, frequency, and duration) on a regional scale [23–26]. Since precipitation is globally one of the predominant freshwater sources, such changes in its regional characteristic can negatively and/or positively influence the economic (e.g., agricultural production), environmental (e.g., soil erosion), and social (e.g., human health hazards) sustainability in different parts of the world [27, 28]. Hence, analysing historical changes in mean and extreme precipitation characteristics can play a key role in the sustainable development of both human life and livelihoods on Earth [29]. According to Irannezhad et al. [30], historical changes in precipitation is crucially important for acting towards achieving the United Nations' 2030 sustainable development goals (SDGs) [31], particularly SDG11 (Sustainable Cities and Communities) and SDG 13 (Climate Action). This is especially true for the cities in developing countries in where changes in precipitation characteristics (in terms of intensity, frequency, and duration) along with poorly managed land-use development practices and unsafe infrastructures [32, 33] can lead to urban flooding events, seriously threatening high human population density [34, 35].

High intensity precipitation events within a few rainy days substantially increased around the world in recent decades, leading to more severe and frequent floods on both regional and local scales [16, 26, 36, 37]. Besides such meteorological conditions, land cover-land use (LCLU) is one of the key physical factors playing a crucial role in flood generation processes [38] by influencing infiltration rates, surface runoff volume, and soil water redistribution behaviour [39]. LCLU changes through urban expansion also cause the global climate to change [40] by replacing the maximum of blue and green space in a region with grey space [41]. In particular, changes in weather and urban space increase the risk of urban flooding by distressing the existing drainage system [34, 35, 42]. Different impacts of intense precipitation in the metropolitan regions are prevalent due to corresponding administration difficulties in handling situations related to downpours, water stagnation, landslide, and mud spate [43]. On the other hand, the significant effects of increasing urban space on microclimate conditions [44] were reviewed for several countries like Egypt [45], China [42], Australia [7], India [46, 47]. Hence, improving our knowledge on changes in extreme precipitation and LCLU is important for developing effective and practical flood mitigation measures, particularly throughout urban areas in developing countries.

India is an agricultural country with 60% of the cultivation reliant on precipitation [48] as the primary freshwater source [49]. All the farming, economy, and development schemes in India are accordingly planned based on spatio-temporal precipitation patterns, which directly influence water availability and need throughout the country [49]. This has already motivated national and international researchers to investigate historical variations and trends in precipitation throughout India considering various time scales (day, month, and season) and spatial ranges (country, state, district, and station) [50]. Accordingly, several studies have attempted to determine significant trends in historical precipitation across entire India [51] as well as its different regions covering Tamil Nadu [52], Andhra Pradesh [53], West Bengal [54], Maharashtra [55], and Assam [49].

In recent times, the exploration of spatial and temporal changes in precipitation and its subsequent outcome on water resources management and agricultural practices have been a hot topic of scientific research around the world [9, 19, 56]. Hence, the analysis of historic precipitation records at the regional level is prime important to know the certainties about the future as well as to prepare suitable mitigation and adaptation strategies [57]. As the distribution of precipitation is not spatially even, it is necessary to have many rain gauge stations scattered throughout the study area to give more accurate and actual records of precipitation [58, 59]. Several investigations on precipitation with respect to space and time have already been done using numerous methods such as frequency analysis [37], probabilistic based analysis [60], homogeneity based analysis [61], and extreme indices [56, 62–64]. Accordingly, the objective of this study was to: (i) investigate variability and trends in annual precipitation over the Madurai Town Planning Area (MTPA), India, during 1976–2019; (ii) analyse seasonal precipitation contributions to such historical variations and trends in annual precipitation; (iii) identify the number of precipitations days and variations in daily precipitation concentration over the study area; and (iv) look for efficient strategies towards sustainable precipitation management in MTPA.

2 Materials and methods

2.1 Study area and data used

Madurai (Fig. 1) is the second-largest and most densely populated city of South India [65–67]. In 2011, the population of Madurai district was about 3,038,252 people; from them, about 15% consider agriculture as the prime source of income. This city is located in a semi-arid region in Tamil Nadu, the southern part of India [68], with an annual average temperature

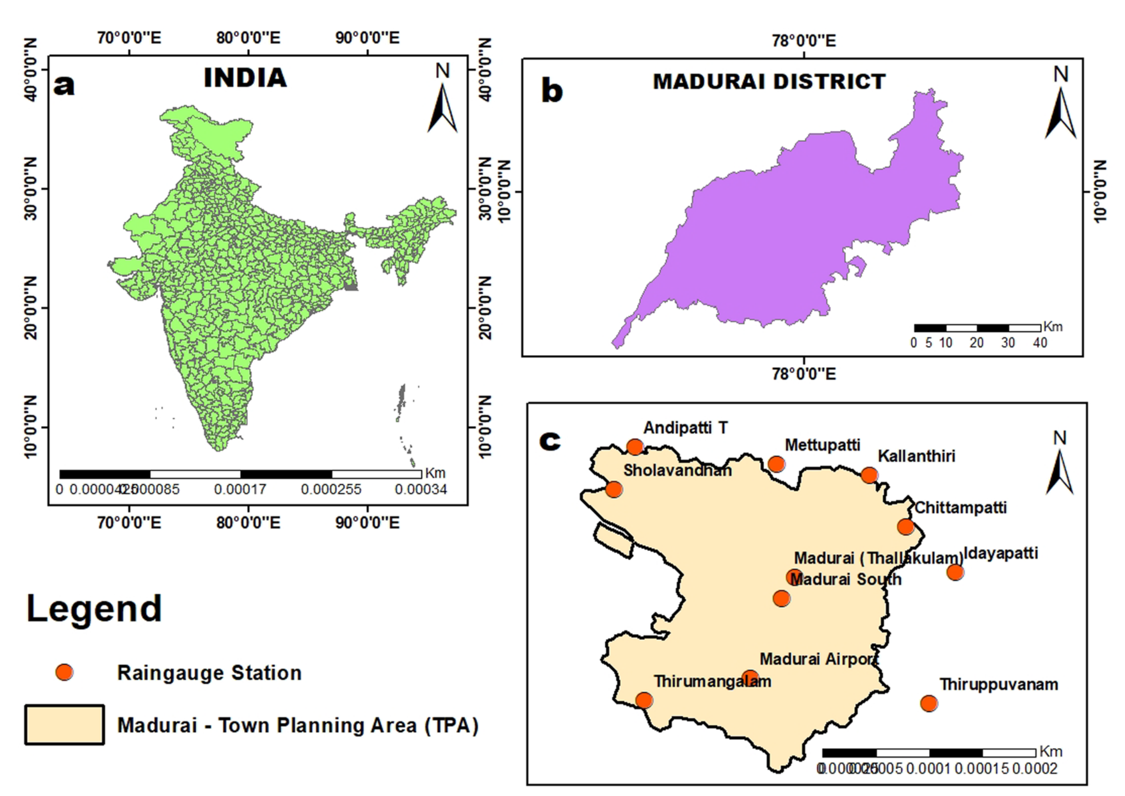

Fig. 1 The geographical locations of **a** India, **b** Madurai district in southern India, and **c** Madurai Town Planning Area (MTPA) and precipitation measurement stations

range of 21.75–38.2 °C [69]. Madurai is on the banks of the River Vaigai, at an elevation of 100 m above the mean sea level [70]. It typically receives precipitation during the Northeast Monsoon (NEM). The annual and monsoonal precipitation events principally show different irregular distribution patterns throughout the southern zone of Tamil Nadu due to its complex geographical features (latitude, longitude, and altitude) [71]. For this region, a few notable studies have previously discussed significant trends in precipitation [72], followed by the cyclic occurrences of severe flooding or drought events [64]. However, a comprehensive analysis of daily precipitation concentration, precipitation days, and monsoon contribution is still needed. On the other hand, in Madurai, the urban space (149 km^2 in 2007) increased (222 km^2 in 2019) primarily due to considerable decreases in the existence of water bodies. In association with significant changes in precipitation patterns, this already put the Madurai Town Planning Area (MTPA) of 726.35 km^2 (Fig. 1c) under stress for proper water resource planning and management.

This study selected 11 hydrometeorological measurement stations in and around the MTPA with historical (1976–2019) daily precipitation records (Table S1 in supplementary information) collected from the State Surface and Groundwater Board, Chennai, India. As all these time series were complete, no gap-filling method was applied.

2.2 Analytical methods

2.2.1 Statistical summary and tests

The descriptive statistics (maximum, minimum, mean, coefficient of variation, standard deviation) of annual precipitation were calculated for each of the hydrometeorological measurement stations selected by this study. Based on the coefficient of variation (CV) values, the annual precipitation time series at these stations were classified from low to extremely high levels [73]. The skewness [49], the kurtosis [74], and the Kolmogorov–Smirnov (K-S) test [75] were applied for exploring if such annual precipitation time series were normally distributed. To detect statistically significant ($p < 0.05$) trends in precipitation time series on different time steps (e.g., annual), the present study employed the Mann–Kendall non-parametric test [76–78]. In the existence of serial correlations in annual, seasonal, and monthly precipitation time series, however, the Modified Mann–Kendall non-parametric trend test [79, 80] was used. Accordingly, the Sen slope was used to estimate the magnitude of such significant trends [81, 82]. The daily precipitation events were categorized into 9 severity levels based on the classification system developed by the Indian Meteorological Department [83]. Besides all these techniques (comprehensively explained in the supplementary information), we also estimated the concentration index (CI) [84] and the precipitation concentration index (PCI) [56] on daily and monthly time scales, respectively. Then, the probability plotting method was used to investigate the frequency of daily precipitation events at each of the hydrometeorological measurement stations selected [85, 86]. The calculation processes of all the CI, PCI, and probability plotting methods were described below.

2.2.2 Concentration index (CI)

The daily precipitation heterogeneity was examined using the CI [84] that measures the distribution of precipitation by determining the percentage of precipitation amount during the precipitation days in each precipitation class interval [87]. The CI values were calculated based on the entire time interval of daily precipitation time series at each of the hydrometeorological measurement stations studied [8]. To calculate the CI, the first step was to arrange the daily precipitation amounts in ascending order at 1 mm intervals from 0 to the maximum. Then, the cumulative percentage of precipitation days was plotted versus the corresponding cumulative percentage of precipitation amounts, with a markedly exponential shape [88]. As the result, the "Lorenz" curve [89] was obtained. The normalized precipitation curve based on the given classification provided the cumulative percentage of precipitation amount (Y) against the cumulative percentage of precipitation days (X) [90]. These curves were based on the following equation:

$$Y = aX\exp(bX) \tag{1}$$

where, a and b are constants, which were calculated by the means of the least-squares method.

Once the constants a and b obtained, the integral of the exponential curve was defined between 0 and 100, which represented the area under the curve, deemed A'. The area over the curve and under the equidistributional line S' was computed through the 5000 area units minus A' [91].

The definite integral of the exponential curve between 0 and 100 expresses the area, A, under the curve, and 5000-A was the area compressed by the curve, Y = X, and X = 100, lets name S. Then, the CI was defined as:

$$CI = {}^{S}/_{5000} \tag{2}$$

The CI measures the relative separation of the exponential curve from the Y = X line. Note that the separation is greater (or CI is higher) when the weight of a few days, the extreme ones, in the total is higher [88]. The value of CI ranges between 0 and 1. The larger area of S means the larger value of CI, indicating the higher concentration [91, 92].

2.2.3 Precipitation concentration index (PCI)

The monthly precipitation heterogeneity [37] was evaluated using the PCI proposed by Oliver (1980) [93] and developed by De Luis et al. (1997) [94]. It was computed using the equation below [82].

$$PCI = \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \times 100 \tag{3}$$

where, P_i represents the monthly precipitation in the month i.

The PCI values: (i) of 10 show a uniform distribution of precipitation (low precipitation concentration); (ii) ranging from 11 to 15 denote a moderate concentration of precipitation; (iii) between 16 and 20 indicate an irregular distribution of precipitation; and (iv) values above 20 express a high precipitation concentration or a strong irregularity in precipitation distribution [11].

2.2.4 Probability plotting method

The purpose of frequency analysis was to measure the relationship between the magnitude of daily precipitation and its probability of exceedance. For the present study, daily precipitation records were arranged in descending order of magnitude at each of the hydrometeorological measurement stations studied. Then each data was assigned an order number (m) which starts from 1 for the first entry to the last event (m = n = number of records). The probability (P) of a daily precipitation event was estimated by the Weibull formula [85, 86]:

$$P = \frac{n}{(m+1)} \tag{4}$$

$$T = \frac{1}{P} \tag{5}$$

3 Result and discussion

3.1 Annual precipitation characteristics

The long-term (1976–2019) average value for annual precipitation at all the hydrometeorological measurement stations studied was about 816 mm, with a standard deviation of 233 mm (Table 1). The highest/lowest standard deviation of annual precipitation (306 mm/173 mm) was found in the Thirupuvanam/Madurai Airport station with the long-term mean annual precipitation of 849 mm/796 mm. The average value of CVs for the annual precipitation time series was about 29% (Table 1), representing their moderate dissimilarity among the stations. The annual precipitation at each station generally represented a moderate range of variation with the CV value less than 30% (Table 1). Exceptionally, at the Thirupuvanam and Idayapatti stations, the annual precipitation showed high and very high levels of variability, respectively (Table 1).

The maximum annual precipitation was about 1565 mm recorded at the Kallanthiri station in 2005, while the minimum (159 mm) was measured at the Thirupuvanam station in 1976 (Table 1). The skewness values of annual precipitation at all 11 hydrometeorological measurement stations showed a range from – 0.026 to 0.839. This indicated that

Table 1 Summary statistics of annual precipitation at all hydrometeorological measurement stations selected by this study

Station	Minimum (mm)	Maximum (mm)	Mean (mm)	Standard Deviation (mm)	CV (%)*	CV Class
Andipatti_T	395	1317	826	230	28	Moderate
Chittampatti	336	1362	789	212	27	Moderate
Idayapatti	196	1273	593	243	41	Very high
Kallanthiri	443	1565	849	243	29	Moderate
Madurai Airport	474	1164	796	173	22	Moderate
Madurai South	398	1311	795	224	28	Moderate
Madurai (Tallakulam)	484	1358	871	237	27	Moderate
Mettupatti	449	1413	836	234	28	Moderate
Sholavandan	437	1434	898	233	26	Moderate
Thirumangalam	488	1349	875	226	26	Moderate
Thirupuvanam	159	1495	850	306	36	High

CV: Coefficient of Variation

Table 2 The results of the skewness, the kurtosis, and the Kolmogorov–Smirnov (K-S) test for annual precipitation time series at each of the hydrometeorological measurement stations selected by this study

Station Name	Skewness	Kurtosis	Z score of skewness	Z score of kurtosis	p value of K-S Test*
Andipatti_T	0.007	−0.995	−0.08964	−1.20798	0.095
Chittampatti	0.592	0.700	1.655462	0.997151	0.200
Idayapatti	0.839	1.056	2.352941	1.505698	0.200
Kallanthiri	0.659	0.358	1.843137	0.508547	0.200
Madurai Airport	0.113	−0.786	0.316527	−1.11823	0. 200
Madurai South	0.201	−0.445	0.565826	−0.63105	0. 200
Madurai (Tallakulam)	0.134	−0.820	0.378151	−1.16809	0.200
Mettupatti	0.582	−0.155	1.553476	−0.21146	0.120
Sholavandan	0.282	−0.311	0.787115	−0.44444	0.200
Thirumangalam	0.569	−0.143	1.416873	−0.18274	0.940
Thirupuvanam	-0.026	−0.009	−0.07283	−0.01282	0.200

K-S: Kolmogorov–Smirnov

the distribution of annual precipitation patterns was asymmetric at each of the stations studied (Table 2). Except for Thirupuvanam, all the stations represented positive skewness values. Similarly, the kurtosis value of annual precipitation datasets at all measurement stations ranged between −0.009 to 1.056 (Table 2). Accordingly, the Chittampatti, Kallanthiri, and Idayapatti stations showed the high peak leptokurtic distribution, while the other stations represented the flat-topped curve with the platykurtic distribution.

In general, for a sample size less than 50, if absolute Z scores for either skewness or kurtosis were less than 1.96, with an alpha level of 0.05, the null hypothesis was accepted and concluded that the sample distribution was normal [74]. Hence, the historical annual precipitation time series were normally distributed from 1976 to 2019 at all hydrometeorological measurement stations studied, except Idayapatti (Table 2). Such findings were also cross-verified with the K-S test at the significance level of 5%. However, the K-S test indicated that the annual precipitation datasets were normally distributed at all the stations except Thirumangalam (Table 2).

Table 3 gives historical (1976–2019) trends (mm yr^{-1}) in annual precipitation at all the hydrometeorological measurement stations studied. On the MTPA-wide scale, annual precipitation shows no statistically significant ($p < 0.05$) changes over time. However, it is inferred that annual precipitation significantly increases at the Andipatti_T (5.7 mm yr^{-1}) and Thirupuvanam (12.6 mm yr^{-1}) during 1976–2019 but decreases at the Madurai South station (−6.3 mm yr^{-1}) (Table 3).

Table 3 The annual precipitation trends (mm yr^{-1}) at all the hydrometeorological measurement stations selected by this study

Station	Sen Slope	p-value	Significant	Trend Direction
Andipatti_T	5.7	0.04	S	Increasing
Chittampatti	0.3	0.98	NS	Decreasing
Idayapatti	2.4	0.38	NS	Increasing
Kallanthiri	0.6	0.88	NS	Increasing
Madurai Airport	−3.7	0.09	NS	Decreasing
Madurai South	−6.3	0.02	S	Decreasing
Madurai (Tallakulam)	−3.4	0.36	NS	Decreasing
Mettupatti	3.9	0.37	NS	Increasing
Sholavandan	−5.4	0.07	NS	Decreasing
Thirumangalam	−2.6	0.32	NS	Decreasing
Thirupuvanam	12.6	0.01	S	Increasing
MTPA-Wide	0.8	0.71	NS	Increasing

S: Statistically Significant ($p < 0.05$)

NS: Statistically Insignificant ($p \geq 0.05$)

3.2 Monthly precipitation and seasonal analysis

There existed intra-annual variations in precipitation across the MTPA. Hence, the seasonality in precipitation records was further investigated using the PCI values on an annual basis. Such PCI values ranged from 11.6 in 2000 at the Idayapatti station to 47.6 in 1999 at the at the Mettupatti station (Fig. 2). Over the study area, the long-term average of PCI values on the annual scale ranged between 18 and 21 (Table S4). On average, about 55, 30, and 17% of the years were fall within the irregular, strongly irregular, moderately irregular classes, respectively. Such irregularity, hence, represented that the majority of annual precipitation was falling within a few months of the year over the entire study area. At the Madurai South, Madurai Airport, Madurai Tallakulam, Chittampatti, Thirumangalam, Thirupuvanam, Kallanthiri, and Mettupatti stations, the monthly precipitation distribution was irregular based on their PCI values ranging between 16 and 20 (Fig. 2). However, the PCI values at the Andipatti, Idayapatti, and Sholavandhan stations exceeded 20, indicating significant irregular precipitation distribution throughout the year.

At each of the hydrometeorological measurement stations studied, the months of September, October, and November together contributed to 54% of annual precipitation, with average monthly precipitation of 118, 181, and 141 mm, respectively (Table 4). The contribution to annual precipitation by each month of April, July, and December ranged between 5 to 6%. With the long-term average value of 69 mm, the May month contributed about 8% to the annual precipitation over the study area. The contribution of January, February, March, and June with average monthly precipitation of 9, 11, 21, and 28 mm, respectively, were between 1 and 3% (Table 4).

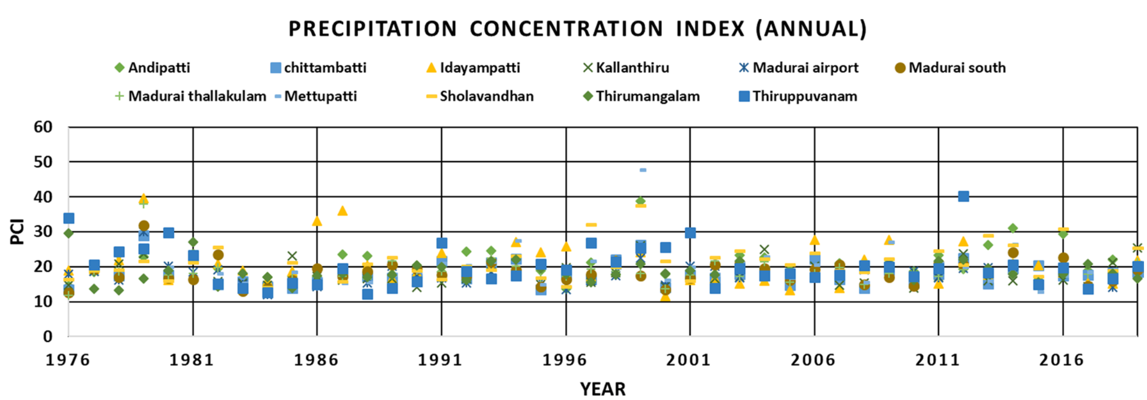

Fig. 2 The precipitation concentration index (PCI) values on the annual scale at all hydrometeorological measurement stations studied

Table 4 The Mann–Kendall non-parametric trend statistics and the Sen's slopes (mm per year) of monthly and seasonal precipitation in the study area during 1976–2019

Time	Average precipitation (mm)	Contribution (%)	Kendall Tau's	Interpretation	p value	Sen slope	Trend
Jan	9.34	1.21	0.08	Increasing	0.52	0.00	No Trend
Feb	10.93	1.37	−0.07	Decreasing	0.59	0.00	No Trend
March	21.45	2.53	−0.06	Decreasing	0.42	−0.01	Insignificant Decreasing
April	49.76	6.11	0.03	Increasing	0.70	0.03	Insignificant Increasing
May	68.54	8.49	0.15	Increasing	0.29	0.74	Insignificant Increasing
June	28.04	3.54	0.08	Increasing	0.45	0.13	Insignificant Increasing
July	48.86	6.19	−0.04	Decreasing	0.46	−0.16	Insignificant Decreasing
Aug	82.42	10.11	0.12	Increasing	0.31	0.81	Insignificant Increasing
Sep	118.67	14.98	−0.08	Decreasing	0.34	−0.67	Insignificant Decreasing
Oct	181.62	22.39	0.08	Increasing	0.44	1.04	Insignificant Increasing
Nov	140.44	16.31	−0.08	Decreasing	0.39	−0.83	Insignificant Decreasing
Dec	45.64	5.60	0.02	Increasing	0.72	0.03	Insignificant Increasing
Winter[a]	20.27	2.58	0.00	Increasing	0.66	0.00	Insignificant Increasing
Summer[b]	139.75	17.13	0.11	Increasing	0.35	1.02	Insignificant Increasing
SWM[c]	277.99	34.82	0.00	Increasing	0.46	0.28	Insignificant Increasing
NEM[d]	367.71	44.30	−0.03	Decreasing	0.49	−0.54	Insignificant Decreasing

[a]Winter (January to February)

[b]Summer (March to May)

[c]SWM: South West Monsoon (June to September)

[d]NEM: North East Monsoon (October to December)

It was visible that the study area received more than 50% of annual rainfall within 3 months of September, October, and November. Based on the Indian Meteorological Department (IMD), the climatological seasons over the study area is generally defined as: Winter (January to February), Summer (March to May), South West Monsoon (June to September), and North East Monsoon (October to December) [50, 83]. Accordingly, the seasonal precipitation analysis indicated that the Northeast Monsoon (NEM), the Southwest Monsoon (SWM), the summer and winter seasons with an average precipitation of 368, 278, 140, and 20 mm contributed about 46, 34, 17, and 3% to annual precipitation across the study area, respectively (Table 4).

Statistically significant ($p < 0.05$) and insignificant ($p \geq 0.05$) trends found in monthly and seasonal precipitation throughout the MTPA during 1976–2019 were given in Table 4. Most of the stations showed insignificant wetting (drying) trends in January (February) (Fig. 3). March showed the Sen's slope value of 0 at all stations, except Idayapatti, Thirumangalam, and Thirupuvanam (Fig. 3). Both April and June months experienced increasing trends at all stations, except Sholavandhan. Historical monthly precipitation increased in May at all stations. August month became wetter at all stations, except Chittampatti. September got dryer in more than 80% of stations. Wetter Octobers were experienced across the study area, except at the Madurai South and Madurai Tallakulam stations. We found negative trends in November precipitation at most of the stations, except Mettupatti, Thirumangalam, and Madurai Tallakulam. The stations of Kallanthiri, Sholavandhan, Madurai South, and Madurai Tallakulam showed negative trends in December precipitation over time. However, all these changes were statistically insignificant ($p \geq 0.05$) (Fig. 3b). Similarly, all serially correlated annual, seasonal, and monthly precipitation time series showed insignificant trends throughout the study area during 1976–2019 (Table 5).

Trend analysis of seasonal precipitation determined that the summer season experienced insignificant positive trends at most of the hydrometeorological measurement stations studied. However, the other seasons (SWM, NEM, and winter) showed an unclear pattern of changes at stations studied. Since the Northeast Monsoon (NEM) season contributed the maximum amount of precipitation to the annual scale, we categorized it into the weak, normal, active, and vigorous monsoons based on the IMD classification system (Table S5). About 20, 47, and 32% of the NEM seasons were active, normal, and weak, respectively (Table S5). The highest value of active monsoon count (11) was recorded at the Thirumangalam station, which is located at an elevation of 127 m. Similarly, for the normal monsoon class, the highest count of

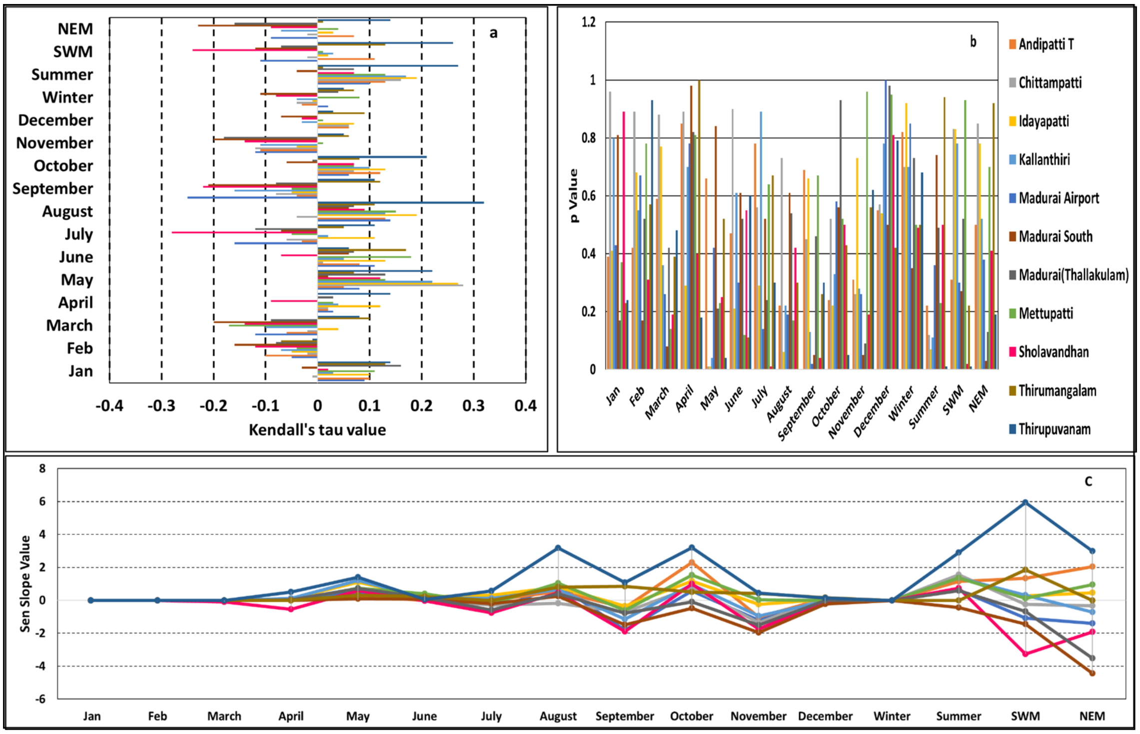

Fig. 3 The results of the Mann–Kendall non-parametric trend test for monthly and seasonal precipitation at all hydrometeorological measurement stations studied. **a** The M–K test value, **b** the p-value, and **c** the Sen's slopes

Table 5 Trends (mm per year) in serially correlated annual, seasonal, and monthly precipitation time series throughout the study area during 1976–2019 based on the Modified Mann–Kendall non-parametric test (Hamed and Rao, 1998)

Station	Time Scale	Sen Slope	Significant
Idayapatti	NEM[a]	1.8	NS*
Sholavandan	Summer[b]	0.5	NS
Thirumangalam	Annual[c]	− 0.11	NS
Thirumangalam	Winter[d]	− 1.1	NS
Thirumangalam	February	− 1.2	NS
Thirumangalam	July	0.0	NS
Thirumangalam	December	− 0.6	NS

[a]NEM: North East Monsoon (October to December)

[b]Summer (March to May)

[c]Annual (January to December)

[d]Winter (January to February)

[*]NS: Statistically Insignificant ($p \geq 0.05$)

23 was recorded at the Madurai Airport, Madurai South, Madurai Tallakulam, and Kallanthiri stations, which are located at the elevations of 133, 136, 136, and 176 m, respectively (Table S5). In the study area, thus, the maximum precipitation received as the orographic type during the NEM season. Accordingly, the mean daily intensity (MDI) of the NEM season precipitation was estimated [95] as below:

$$MDI = \frac{Average\ Seasonal\ Precipitation}{Number\ of\ Precipitation\ Days} \tag{6}$$

The highest (53 mm) and lowest (32 mm) values of MDI were recorded at the Sholavandhan and the Idayapatti stations, respectively (Table S5). The peri-urban regions had red sandy loam soil, with an infiltration capacity of 0.002 mm per s [96]. Hence, in dormant season at normal conditions (AMC II), the runoff generated from the MDI might be in the range of 4 to 25 mm, while the MDI was not sufficient to make any runoff during the growing season. However, in urban space, more than 80% of precipitation reaching the surface could be generated as runoff due to the influence of building interception, atmospheric vaporisation, and dispersion.

This study further identified normal, flood, and drought years based on the NEM season precipitation time series by employing the method adopted by Parthasarthy et al. [97] and Singh [98]. Accordingly, the flood year was defined as (R + S) or more, while the drought year was (R − S) or less, where R was the average seasonal precipitation across the study area during 1976–2019, and S was the standard deviation. On average, the study area experienced 30, 7, and 6 years of normal flooding and drought conditions, respectively.

3.3 Analysis of daily precipitation concentration

The number of days with measurable (≥ 0.1 mm) amount of precipitation (hereafter "precipitable days") was between 388 to 2654 days, leading to total precipitation from 5,603 to 31,221 mm at the selected station during their full study periods. Among all 14,600 days of precipitation measurements, the highest record of precipitable days (2654) was found at the Madurai Airport station, followed by 1972 and 1426 precipitable days at the Thirumangalam and Thirupuvanam stations, respectively. However, the precipitable days at the other stations were less than 1000. Similarly, the maximum total precipitation amount (31,221 mm) was recorded at the Thirumangalam station, followed by the Madurai Airport (26,785 mm) and the Thirupuvanam (25,066 mm) stations. The total precipitation amounts were around (less than) 10,000 mm at the Madurai South and the Sholavandhan (the other) stations.

The Andipatti station received 6629 mm of total precipitation in 388 days, while the Thallakulam station received almost the same amount (6881 mm) in 586 days. Though the difference in precipitable days between these two stations was about 200, the difference in their total precipitation amounts was only about 250 mm. Similarly, such differences at the Mettupatti and Chittampatti stations were about 320 days. Hence, the station with less precipitable days could receive higher precipitation amounts than those stations with a higher number of precipitable days. The maximum daily precipitation recorded at each station ranged between 99.4 mm and 287 mm, and was typically experienced during November (Table S6).

The annual number of precipitation days ranged between 9 and 140 (Fig. 4), with the annual precipitation amounts of 176 and 772 mm, respectively. On average, about 52 days (14%) of the year contributed to the total precipitation across the study area. A day with a precipitation amount of 2.5 mm or more was considered a rainy day (hereafter, "precipitation day") based on the [83]. Over the study area, the annual precipitation days ranged between 9 and 71 (Fig. 4), with the corresponding annual precipitation amounts of 179 mm at Thirupuvanam station in 1980 and 1351 mm at the Chittampatti station in 1977, respectively. Only about 11% days of the year contributed to the precipitation days. At the Madurai Airport station, about 57% of precipitable days were precipitation days, while it was about 70–90% at the other stations. On an average, about 81% of precipitable days were precipitation days. In general, the highest number of precipitation days was sequentially recorded in October (21%), November (17%), September (14%), August (10%), and May (9%) (Table S7). Accordingly, the maximum precipitation days were seen in order of the NEM > SWM > Summer > Winter seasons, with the average values of 19, 15, 8, 2 days contributing to the 45, 36, 19, 5% of total precipitation days, respectively (Table S7).

A constant series of CI values, ranging between 0.54 and 0.58, were found for daily precipitation throughout the study area, while the Madurai Airport station alone showed a CI value of 0.66 (Table 6). The CI values of daily precipitation in

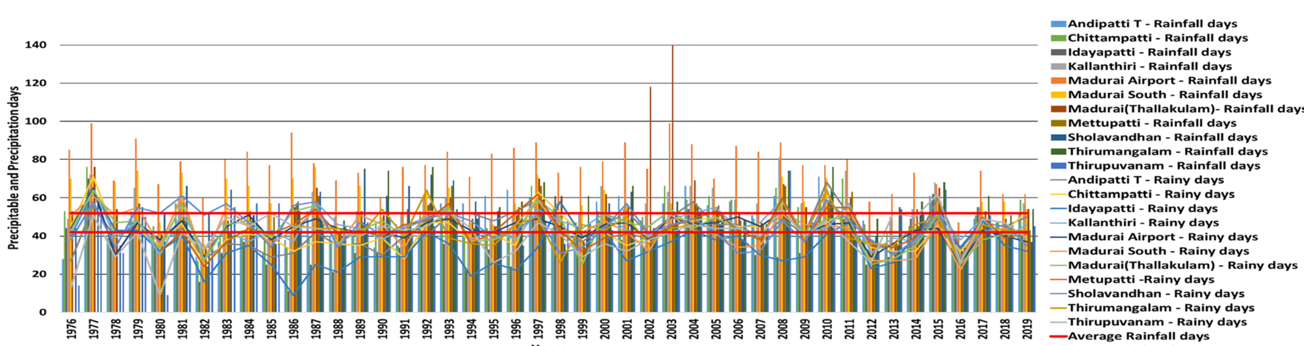

Fig. 4 The annual number of precipitable and precipitation days at all selected hydrometeorological measurement stations during their study periods given in Table S1

Table 6 The concentration index (CI) of daily precipitation at all the hydrometeorological measurement stations studied

Station Name	a	b	r^2	A	S	CI	P* by 25% N
Andipatti_T	0.08	0.02	1.00	2278	2722	0.54	62.7
Chittampatti	0.07	0.03	1.00	2269	2731	0.55	62.2
Idayapatti	0.09	0.02	0.99	2308	2692	0.54	61.5
Kallanthiri	0.07	0.03	1.00	2240	2760	0.55	65.9
Madurai Airport	0.02	0.04	0.99	1710	3290	0.66	76.2
Madurai South	0.05	0.03	0.99	2137	2863	0.57	67
Madurai (Tallakulam)	0.06	0.03	1.00	2214	2786	0.56	71.8
Mettupatti	0.08	0.03	0.99	2259	2741	0.55	64.8
Sholavandan	0.07	0.03	1.00	2233	2767	0.55	65.8
Thirumangalam	0.05	0.03	1.00	2111	2889	0.58	67.2
Thirupuvanam	0.07	0.03	1.00	2242	2758	0.55	63.0

*Precipitation amounts greater than 12 mm was considered for this analysis

5 out of all 11 selected stations was about 0.55, representing 25% of precipitable days contribution was between 62 and 65%. The minimum CI value was 0.54 at the Andipatti and the Idayapatti stations, where 25% of precipitable days contributed to 62.7 and 61.5% of precipitation. The maximum CI value of 0.66 was noted at the Madurai Airport station, where 25% of precipitable days contribute to 76.2% precipitation. With a comparison of these maximum and minimum CI values, it was obvious that annual precipitation at the Madurai Airport station (with a higher CI value) was more concentrated on less precipitable days during the year than in the remaining stations (Table 6). Based on such CI values, different levels of irregularity existed with the daily precipitation concentration.

According to the Lorenz curve (Fig. S7), the minimum daily precipitation, ranging from 0.1 to 0.9 mm, was mostly recorded at the Madurai Airport station with the total precipitable days of 719. The maximum daily precipitation of 243 mm was recorded at the Sholavandhan station. Six stations (Thirumangalam, Madurai Tallakulam, Chittampatti, Madurai South, Madurai Airport, and Kallanthiri) showed the highest precipitation amount recorded in the range of 0.1–0.9 mm. At the other station (Sholavandhan, Idayapatti, Mettupatti, Andipatti, and Thirupuvanam), however, the highest amount was found in the range of 2–6 mm. Based on the CI, the average of precipitable days was 52 days, and thus, its 25% (13 precipitable days) contributed about 60–70% to annual precipitation across the study area. Accordingly, there was no precipitation for nearly 310 days of the year and about 80% of the precipitable days were precipitation days.

Table 7 The number (days) and the total amount (mm) of different daily precipitation classes (Table S3) at all hydrometeorological measurement stations studied

Station	Daily Precipitation Class															
	T		VLR		LR		MR		RH		HR		VHR		EHR	
	N	P	N	P	N	P	N	P	N	P	N	P	N	P	N	P
Andipatti_T	0	0	5	8	13	63	23	399	4	208	2	132	1.00	160	0.00	0
Chittampatti	0	0	7	11	14	67	22	383	5	210	1	116	0.00	0	0.00	0
Idayapatti	0	0	4	7	12	57	18	307	3	128	1	83	0.068	9	0.00	0
Kallanthiri	0	0	11	17	20	97	28	448	5	230	1	103	0.114	17	0.00	0
Madurai Airport	0	0	29	26	15	70	22	370	4	201	2	125	0.045	7	0.00	0
Madurai South	0	0	12	16	15	72	22	374	5	223	1	95	0.045	7	0.00	0
Madurai (Tallakulam)	0	0	11	14	14	67	22	383	6	257	2	128	0.114	19	0.00	0
Mettupatti	0	0	5	8	15	71	22	387	5	212	2	129	0.15	25	0.00	0
Sholavandan	0	0	6	10	14	70	23	396	5	257	2	134	0.159	22	0.02	7
Thirumangalam	0	0	9	12	14	61	20	338	5	248	1	121	0.00	13	0.00	0
Thirupuvanam	0	0	4	7	12	56	21	367	5	229	2	152	0.00	22	0.00	0

Check Table S3, for the definition and abbreviations of each daily precipitation class

N: Number of days

P: Amount of precipitation

During 1976–2019, the amount of precipitation received across the study area mainly consisted of moderate (46%), rather heavy (26%), heavy (15%), light (8), very heavy (3%), and very light (1%) precipitation classes (Table 7). However, the contributions of both trace and extreme precipitation classes were insignificant. On average, the number of very light, light, moderate, rather heavy, and heavy precipitation events was about 9, 14, 22, 5, and 2 days, respectively (Table 7). Hence, (i) the light precipitation events maintained a constant trend throughout the year; (ii) the moderate precipitation days showed an increasing trend; (iii) the rather heavy events decreased; and (iv) the heavy rain class become more frequent. On the seasonal scale, the precipitation amount was mainly (87%) consisted of moderate, rather heavy, heavy, and light precipitation classes (Table S8). Accordingly, the NEM season had the maximum contribution these four classes, followed by the SEM > Summer > Winter seasons (Table S8).

The average annual precipitation corresponding to the 25, 50, 75, and 90% probability were about: (i) 405, 342, 271, and 216 mm for the moderate range intensity; (ii) 289, 208, 130, and 65 mm for the rather heavy class; (iii) 186, 101, 25, and 0 mm for the heavy range; (iv) 20, 13, 10, and 8 mm for the very light class; (v) 107, 69, 53, and 38 mm for the light range intensity, respectively (Figs. 5 and S2). The return period of the discussed dependable rainfall was 4, 2, 1, 1 year(s) respectively. Dependable rainfall was defined as the rainfall, which can be expected in a set number of years out of a total number of years [99]. The maximum dependable precipitation for moderate and light rain classes was recorded at the Kallanthiri station, while for heavy class at the Thirupuvanam station. The highest value of the very light range was recorded at the Mettupatti and Idayapatti stations. The dependable percentage of average precipitation of very heavy class at the Chittampatti, Idayapatti, Mettupatti, Madurai South, and Madurai Airport, Madurai Tallakulam stations ranged 1–3%. At the Sholavandhan, Andipatti, Kallanthiri, Thirupuvanam, and Thirumangalam stations, the dependable percentage of average very heavy rainfall class was 1–7%, with the return period was ranging from 7 to 45 years.

3.4 Strategy for effective management of precipitation

3.4.1 Agriculture

Paddy, oil seeds-groundnut, pulses (Sorghum and Maize), cotton, banana, sugarcane, vegetables (bhendi, brinjal), and fodder grass are the commonly cultivated crops in the region (TNAU). In the north portion of our study area covering the Madurai North, Melur, Usilampatti, and Vadipatti taluks, agriculture is generally dependent on the water released through lined channels from the Vaigai dam as the source of irrigation. The surplus water from the Vaigai dam is also discharged through the Periyar main channel. The discharge of water through the canal for irrigation has been reduced from 568

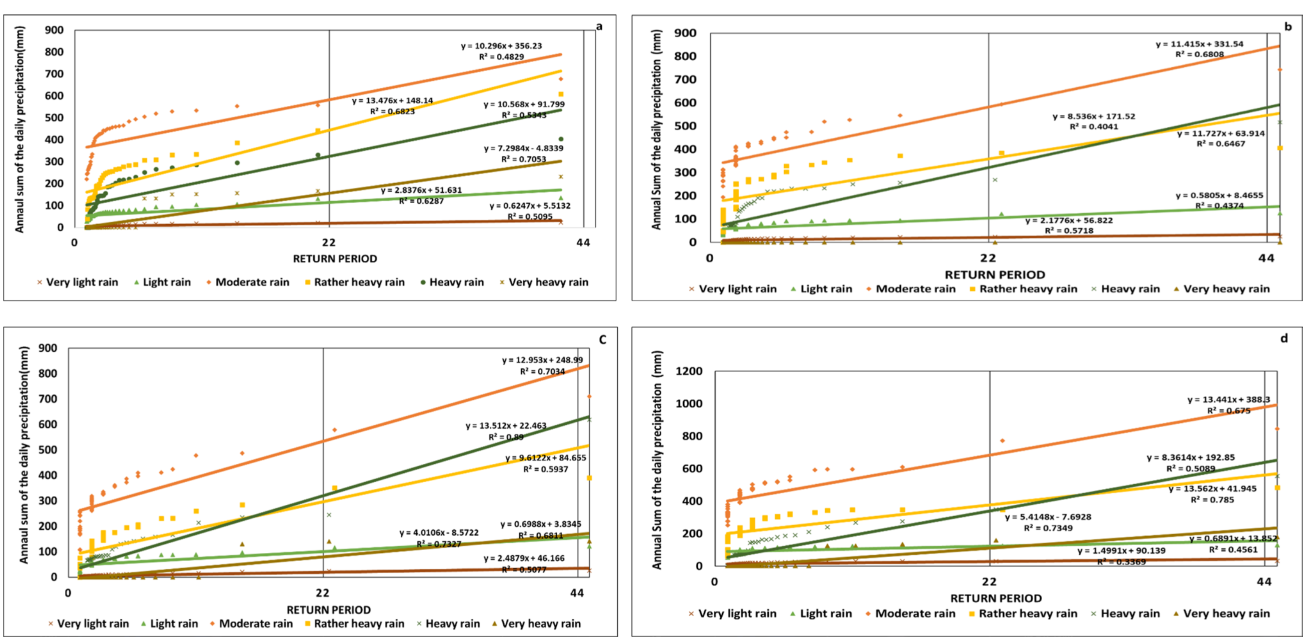

Fig. 5 The probability plotting of different daily precipitation classes (Table S3) at **a** Andipatti, **b** Chittampatti, **c** Idayapatti, and **d** Kallanthiri stations

cusec/day in 2013 to 460 cusec/day in 2018 [70]. Hence, people in this region are now dependent on system tanks for irrigation during the days of water shortage. These system tanks receive water from rainfall through runoff in catchment areas. In the south portion of the study area covering Madurai South, Thirumangalam, Kariapatti, and Manamadurai taluk, precipitation is the main source of water for irrigation and is collected through runoff in nonsystem tanks. With monsoon failure, the people in the region are depending on groundwater and wastewater for different irrigation purposes.

Considering the average effective precipitation of each month and crop water requirement of those predominant crops (based on FAO norms), the irrigation water need for these regions was estimated (Table 8). We found from the analysis that, except October, the monthly precipitation received was in deficit to meet the irrigation water requirement. Hence, the contribution of water through subsurface recharge was much higher than runoff from the agricultural land in the study area.

3.4.2 Urbanisation

It is expected that urban space may increase to 222 km^2 from the existing area of 149 km^2. Hence, the potential for urban runoff will be high. In the case of the north portion, storm channels can collect the runoff from urban space, fill the system tanks, and then, discharge the surpluses into the Vaigai River. Similarly, in the southern zone also exist stormwater drains, which can collect surplus water from the Vaigai River along with the runoff from the catchment areas, and fill the system tanks. But due to the lack of a proper drainage network to collect wastewater from the houses in the region, these channels are now carrying wastewater. Now, the government has taken initiative to restore these channel systems, which will play a critical role in the runoff management of the city. The region is suitable for the construction of various artificial recharge structures such as percolation ponds, check dams, and sub-surface dykes [100]. Identification of location for execution of such structures requires further investigation on lineament, geomorphological, drainage pattern of the region. The type of aquifer over the region is hard rock and alluvial formation. The region with hard rock aquifer has low hydraulic conductivity and good storage capacity, and thus, are the best suitable for artificial recharge than alluvial formation. As alluvial formation has more hydraulic conductivity, the movement of water is higher than the possibility for holding. Hence, the planting of trees in these aquifer zones will enhance the water levels in the region.

On the other hand, by the implementation of rainwater harvesting at each house, we can collect 1000 L of water every year from a square meter of area [101]. There is totally 486,611 number of houses in the Madurai North and South zones. If the rainwater harvesting system is implemented in all the houses, it is possible to collect 0.3 million litres of water every year in the subsurface.

$$\text{Rainwater harvesting potential} = \text{rainfall} * \text{collection efficiency} \tag{7}$$

Average Annual Rainfall = 0.816 m.
Area of roof catchment = 100 m^2 (assumption).
Volume of rainfall over the plot = 0.816 * 100 = 81.6 m^3 = 81,600 L.
Approximate rainwater collection efficiency = 81,600 *0.8*0.85 = 55,488 L.
Where, 0.8 = coefficient of roof surface, 0.85 = coefficient of evaporation,
Hence, for all the households = 486,611* 55,488 = 27,00,10,71,168 L = 27 Mm.^{3}
In addition to the above, the following additional strategies can be adopted:

Table 8 Monthly irrigation water requirement and precipitation contribution in the study area (MTPA)

Crop	Growth Months	Water Need (mm/month)	Jan (mm/month)	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maize	4	136	−141	−140	−133	−117	−105	−117	−95	−95	−66	−16	−49	−119
Sugarcane	12	123	−128	−127	−120	−103	−92	−104	−82	−82	−53	−3	−36	−106
Banana	12	99	−103	−102	−96	−79	−68	−79	−58	−58	−29	22	−11	−81
Cotton	7	108	−112	−111	−105	−88	−77	−88	−67	−67	−38	13	−20	−90
Sorghum	4	104	−108	−107	−101	−84	−73	−85	−63	−63	−34	16	−16	−86
Paddy	5	90	−94	−93	−87	−70	−59	−71	−49	−49	−20	30	−3	−73

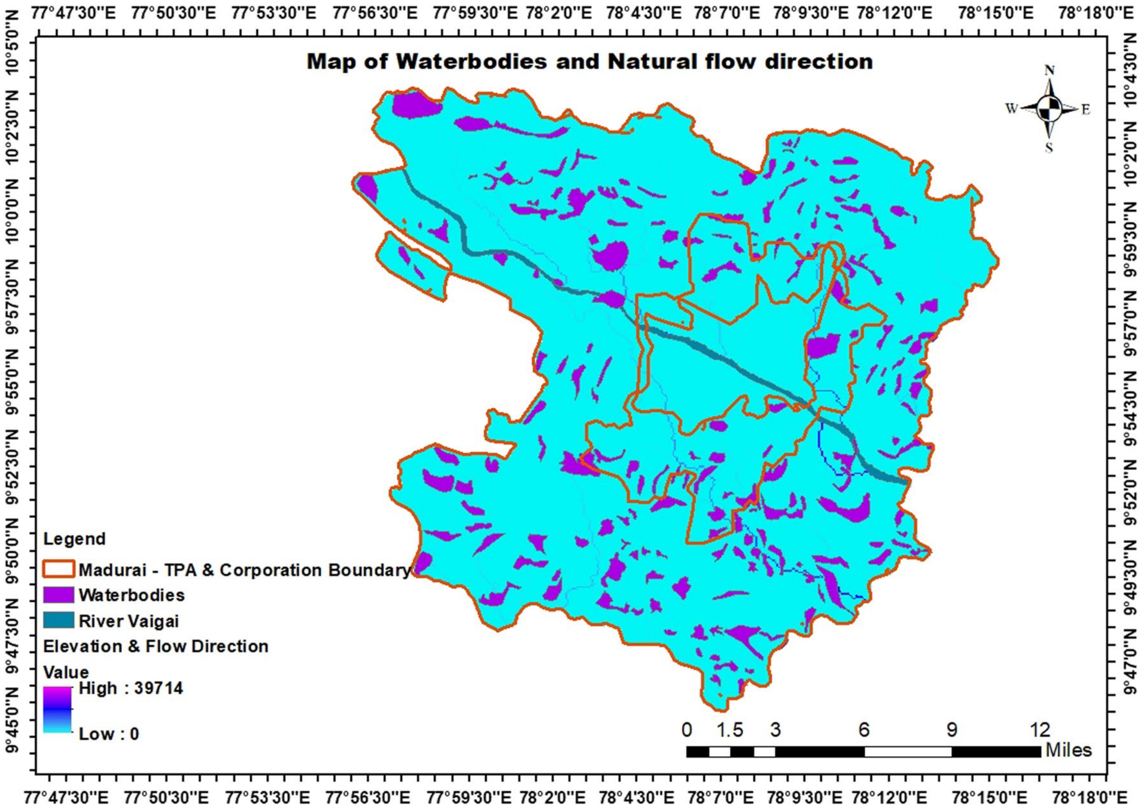

Fig. 6 Flow direction and waterbodies in the study area

a) Increasing/efficient management of existing water intake and storage structures: There exist a total 212 waterbodies (Fig. 6), with each waterbody area ranging from 1.7 to 281 hectares. In addition to it, the Vaigai River, which runs 32 km along the study area, will receive water only during monsoon seasons. The remaining duration of the year, the rainfall received in the region can be collected by providing recharge structures within the river bed.
b) Control water movement over the soil surface: The predominant types of soil in the region are red and black soil, with sandy loam or sandy clay loam type. As per hydrological soil group classification, sandy loam soil comes under the group of soil class A, with low runoff potential (infiltration rate 7.62 mm/h). However, the sandy clay loam (infiltration rate 1.27 mm/h) type is in group C, with high runoff potential [102]. The northwest and north portions of the region are elevated at 352 m, while the areas in the south and southeast directions are located at elevations up to 108 m. The runoff from the region during monsoon season gently moves along the southeast direction (Fig. 7). There exists a wide portion of open space as barren and scrubland along the boundary of the study area in the southeast direction. If these wastelands can be effectively used for vegetation or agro-foresting, the water that infiltrates during precipitation can be prevented from subsurface movement; thus, enhancing the groundwater level.

4 Conclusions

The major substantial effect of climate change and global warming was visible in the water cycle through changes in precipitation frequency and magnitude. Previous studied had also reported different significant effects of increasing urban space on microclimate conditions around the world. Hence, this study investigated annual, monthly, and daily precipitation at 11 hydrometeorological measurement stations located in and around the Madurai Town Planning Area (MTPA) in India during 1976–2019. The following major conclusions were drawn:

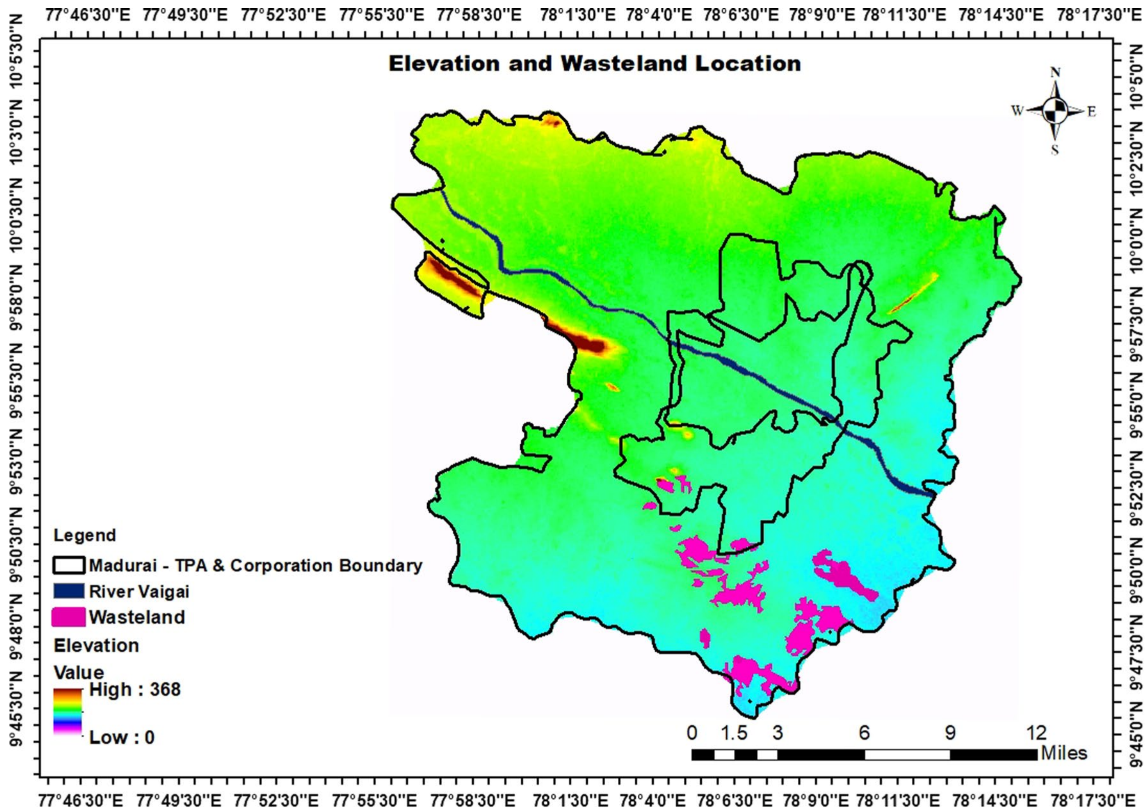

Fig. 7 The elevation and wasteland region of the study area

1. The KS test confirmed that the data is normally distributed at $p = 0.05$. The Mann–Kendall non-parametric test determined no statistically significant ($p < 0.05$) changes in annual precipitation over the MTPA during 1976–2019. The PCI analysis confirmed the intra-annual precipitation variability over the region. Such irregularities showed an increasing trend, and thus, the higher possibility of increases in the seasonality of precipitation.
2. Across the study area, about 50% of annual precipitation was received within the 3 months of September, October, and November. Monthly precipitation showed drying trends in March, July, September, and November, which contributed 2.5, 6.1, 14, 16% to the annual precipitation. Similarly, seasonal analysis represented the NEM as a major source of water for the region, contributing 44% to the annual precipitation. The decreasing trend in the NEM season precipitation insisted on the possibility for increases in weak monsoons over the region in the near future. The monsoon rainfall analysis also indicated 15% probability of occurrence of flood or drought over the MTPA.
3. Out of 365 days of the year, the total precipitable days was 52 days, with 81% of it as precipitation days. The CI values (0.54 to 0.66) showed that nearly 60–70% of precipitation was received within 25% of precipitation days. The most frequent precipitation events were in the moderate (46%) and the rather heavy (26%) classes, which increased over time. The probability plotting determined the 75% dependable average annual precipitation of the above-mentioned classes were 271 and 130 mm, respectively, with a recurrence period of 1 year.
4. Beside the water from the Vaigai dam, precipitation is the predominant source of water for people in the region for both domestic and agricultural purposes. Considering the common crops cultivated in the region, the normal annual precipitation will not be sufficient to make runoff from the agricultural fields, except in October. There also exists a deficit in terms of irrigation water requirements. Therefore, precipitation is probably not sufficient to meet possible higher agricultural demands in the near future. Hence, conservation practices must target urban stretch and open spaces in the study area.
5. In urban spaces, rainwater harvesting must be applied as it is estimated that approximately 27 Mm^3 of water can be preserved from runoff by implementing such structures at the household level. Throughout the study area, the Vaigai River and 212 waterbodies are golden treasures that hold the precipitation and recharge the subsurface. Hence, suitable recharge structures can be implemented along the river stretch and in the waterbodies. Considering the

slope pattern, the open space, and the barren land located along the southeast direction of the study area can be used for agro-forestry to prevent both surface and subsurface runoff from the region.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by SRT, and KV. The first draft of the manuscript was written by SRT and SC. US, MI, AA contributed data interpretations, result discussion and manuscript reviewing and fine tuning. All authors read and approved the final manuscript.

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Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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