



RESEARCH ARTICLE

# Hydrological trends and agricultural water footprint in the Pennaiyar basin, Tamil Nadu

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## Abstract

India is currently facing one of its biggest challenges - the world's worst water crisis. With only 2.5 % of India's water resources, Tamil Nadu's water demand is rising due to increasing population, rapid urbanisation, variability in rainfall patterns and climate change, apart from agricultural water demand. In this context, the present study aims to assess the hydrological behavior of the Pennaiyar river basin located in the eastern part of Tamil Nadu, India. The assessment includes spatial and temporal analysis of rainfall and evapotranspiration (ET), dynamic evaluation of groundwater status and estimation of crop water footprint (WFP) for major crops in the basin. Results revealed that the average annual rainfall in the Pennaiyar river basin is approximately 927 mm. Seasonal rainfall distribution was 15 % in summer, 43 % during the southwest monsoon, 34 % during the northeast monsoon and 8 % in winter. Using the Hargreaves-Samani model, reference evapotranspiration (ET<sub>0</sub>) was found to range from 3.5 mm/day to 6.4 mm/day. The green WFP for paddy, maize, groundnut and sugarcane was 534 m<sup>3</sup>/t, 318 m<sup>3</sup>/t, 980 m<sup>3</sup>/t and 41 m<sup>3</sup>/t respectively. Similarly, the blue WFP for these crops was 500 m<sup>3</sup>/t, 177 m<sup>3</sup>/t, 592 m<sup>3</sup>/t and 54 m<sup>3</sup>/t respectively. The categorization of groundwater firkas (unit of Taluk) (2020, 2022 and 2023) in the Pennaiyar basin was done as over-exploited, critical, semi-critical and safe. In 2023, it was observed that there were 110 over-exploited firkas, 22 critical firkas, 61 semi-critical firkas and 63 safe firkas. The study emphasizes sustainable water management strategies for the Pennaiyar basin.

**Keywords:** evapotranspiration; groundwater; rainfall; spatio-temporal analysis; sustainability; water footprint

## Introduction

The United Nations introduced 17 sustainable development goals (SDGs) to tackle global challenges and create a sustainable future by 2030. One of these, SDG 6: Clean Water and Sanitation, focuses on ensuring that everyone has access to safe water and proper sanitation (1). A key target under this goal, SDG 6.5, calls for better water management at all levels.

In India, agriculture uses about 81 % of the country's water resources (2). In Tamil Nadu, farming is an important part of both the economy and people's livelihoods. Due to population growth, higher food demand, global warming and climate change, agriculture now needs even more water to meet crop evapotranspiration (ET) requirements (3, 4). Climate change directly affects rainfall patterns and crop ET, making it important to study changes in rainfall to manage water resources effectively (5). The way rainfall varies across time and location is crucial for deciding cropping patterns and ensuring sustainable farming (6, 7).

Crop ET plays a crucial role in improving how efficiently water is used in irrigation (8). Estimating it correctly is important for good irrigation planning. Several indicators help measure water and food sustainability, including the water footprint (WFP), water

scarcity and crop water productivity (9). The WFP is a relatively new concept that looks at water use from both production and consumption angles (10). It measures the total amount of freshwater used to produce goods and services, usually expressed in cubic meters per tonnes (m<sup>3</sup>/t) or litres per kilogram (L/kg). It is now widely seen as a useful tool for ensuring water is used efficiently, fairly and sustainably (11). Research has shown that understanding changes in crop ET is essential for properly assessing the crop WFP (12-14).

Groundwater, a key freshwater source, is being overused for household, farming and industrial needs. This has led to a sharp decline in groundwater levels, especially in dry and semi-dry areas (15, 16).

Geospatial technologies are commonly used to study the spatial and time-based changes in water-related factors like surface water, underground water and groundwater (17-19). Many recent studies have examined rainfall trends, crop ET, WFP and groundwater conditions across different regions (20-22). These studies are important for sustainable water management, including better irrigation planning and improving farm productivity.

This research aims to analyse how rainfall, ET, crop water use (CWU), crop WFP and groundwater levels change over time and across different locations in the Pennaiyar basin, Tamil Nadu.

## Materials and Methods

### Study location

Among 17 major river basins in Tamil Nadu, the Pennaiyar basin (Fig. 1) is chosen in this study. The Pennaiyar basin comprises parts of Dharmapuri, Krishnagiri, Tiruvannamalai, Vellore, Villupuram and Salem districts of Tamil Nadu and covers a total area of 11250 sq. km. It is bounded by Karnataka state in the north, west and northwest and by Andhra Pradesh in the northeast. In other words, it is bounded by the Cauvery basin in the south and southwest and by the Palar basin in the northeast. Agriculture dominates the region, with 2 main seasons: *Kharif* and *Rabi*. Major crops include paddy, maize, groundnut and sugarcane.

### Spatial and temporal analysis of rainfall patterns

Rainfall is the key component in the hydrologic cycle and is estimated in all water management and crop planning studies. The time series analysis of rainfall data obtained from the NASA Power Website (1989-2023) for 35 years was conducted. The average annual rainfall, average monthly rainfall and seasonal changes in the rainfall were estimated. Using the inverse distance weighted (IDW) interpolation tool in ArcGIS, the spatial variation of average monthly rainfall was estimated for the Pennaiyar basin.

### Spatial and temporal analysis of reference evapotranspiration (ET<sub>0</sub>)

ET<sub>0</sub> is the key component in the hydrologic cycle and is estimated in all water management and crop planning studies. In this study, the Hargreaves-Samani model was used for the estimation of ET<sub>0</sub>. Based on the maximum and minimum temperatures, the Hargreaves-Samani model estimates the ET<sub>0</sub>. The maximum and minimum temperature data for the study area were obtained from the NASA Power Website (1989-2023).

$$ET_0 = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} R_a$$

Where T<sub>max</sub> and T<sub>min</sub> are the maximum and minimum daily temperatures, T<sub>mean</sub> is the daily mean temperature and R<sub>a</sub> is the extraterrestrial radiation. The average monthly ET<sub>0</sub> was estimated by using the above ET<sub>0</sub> model. Using the inverse distance weighted (IDW) interpolation tool in ArcGIS, spatial variation of ET<sub>0</sub> was done for the Pennaiyar basin.

### Estimation of crop evapotranspiration

The crop ET was estimated as the product of ET<sub>0</sub> and the crop coefficient. It is given by the following equation:

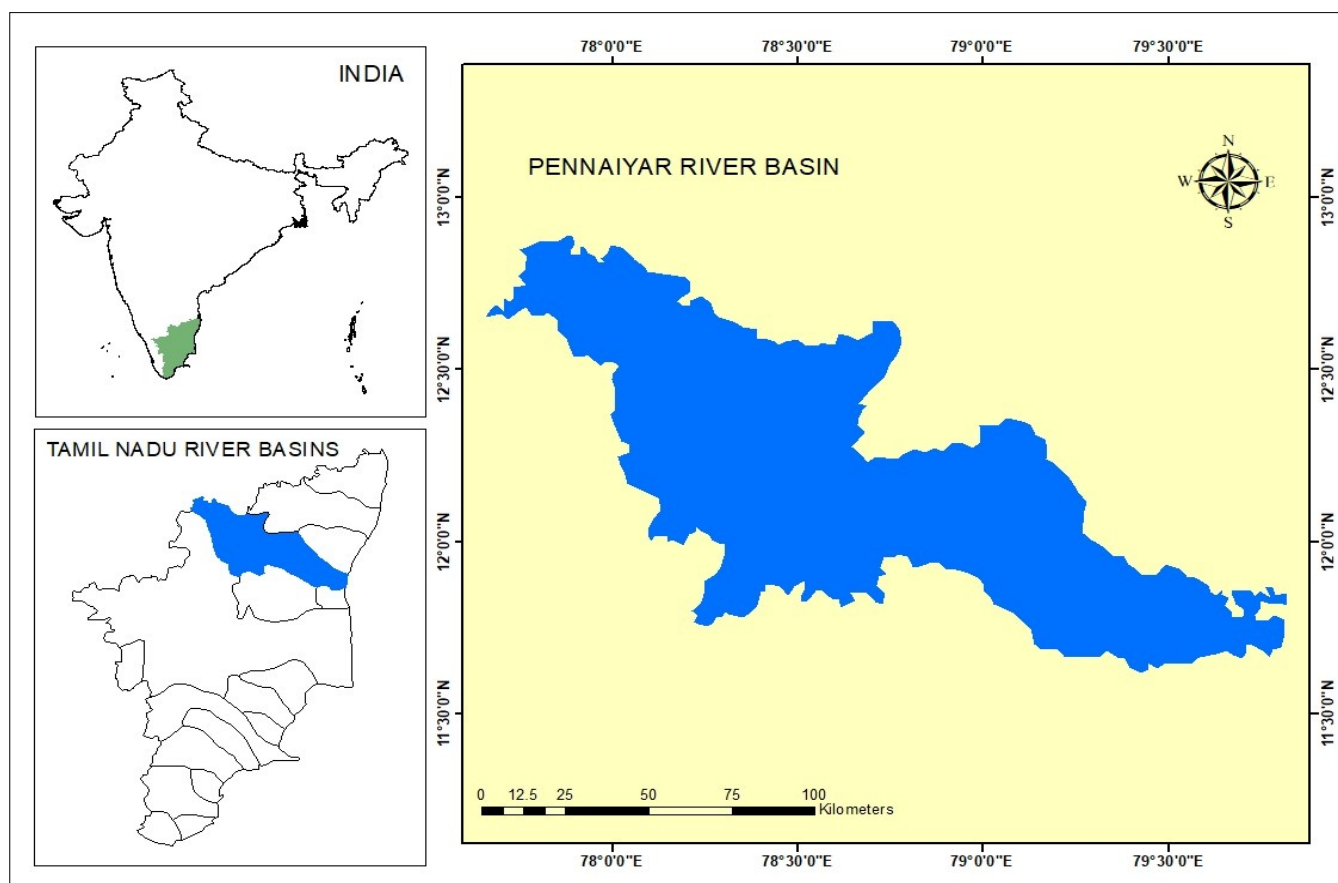
$$ET_c = ET_0 * K_c$$

Where, ET<sub>c</sub> = actual crop evapotranspiration rate; K<sub>c</sub> = crop coefficient; ET<sub>0</sub> = reference evapotranspiration calculated using the Hargreaves' Method. The crop coefficients for major crops grown in the study area at different stages are taken from FAO Guidelines for computing crop ET (23).

### Estimation of crop water footprint (WFP)

The green water evapotranspiration (ET<sub>green</sub>) was calculated as the minimum of ET<sub>c</sub> and effective rainfall (P<sub>eff</sub>), with a 10-day time step. The total green water evapotranspiration is obtained by summing up ET<sub>green</sub> over the growing period. It is given by the following equation (10).

$$ET_{green} = \min(ET_c, P_{eff})$$



**Fig. 1.** Location of the study area.

$$ET_{blue} = \max(0, ET_c - P_{eff})$$

The blue water evapotranspiration ( $ET_{blue}$ ) is estimated as difference between the  $ET_c$  and the  $P_{eff}$  daily.

When the  $P_{eff}$  is greater than the  $ET_c$ ,  $ET_{blue}$  is equal to 0. The total blue water evapotranspiration is obtained by adding  $ET_{blue}$  over the whole growing period.

The WFP of a product is defined as the total volume of fresh water that is used directly or indirectly to produce the product. The factor "10" is used to convert ET in mm to cubic meters per hectare ( $m^3/ha$ ) and is called CWU. This conversion is standard in WFP studies, as 1 mm of ET over 1 ha equals  $10 m^3$  of water.

$$CWU_{green} = 10 * ET_{green}$$

$$CWU_{blue} = 10 * ET_{blue}$$

The green component in the process WFP of a crop ( $WF_{proc, green}, m^3/t$ ) was calculated as the green component in crop water use ( $CWU_{green}, m^3/ha$ ) divided by the crop yield  $Y$  (t/ha). The blue component of WFP ( $WF_{proc, blue}, m^3/t$ ) was also calculated from the blue component in crop water use ( $CWU_{blue}, m^3/ha$ ) similarly. The equations used are listed below:

$$WF_{proc, green} = \frac{CWU_{green}}{Y}$$

$$WF_{proc, blue} = \frac{CWU_{blue}}{Y}$$

### Dynamic assessment of groundwater status

Groundwater potential assessment is a dynamic one and not static. This is due to several factors like the number of wells, average rainfall, total recharge, irrigation methods and cropping pattern. The groundwater resources in Tamil Nadu were assessed on a level basis and in these assessments, the assessing unit is firka (unit of Taluk). The firkas are categorized as overexploited (more than 100 % extraction), critical (90 % to 100 % extraction), semi-critical (65 % to

90 % extraction), safe (less than 65 % extraction) and saline firkas. The first level comparison was made for the districts covered by the Pennaiyar basin.

## Results and Discussion

The long-term analysis of rainfall in the Pennaiyar basin from 1989 to 2023 shows that the average annual rainfall was around 927 mm. As illustrated in Fig. 2, the highest annual rainfall was in 2021, measuring 1479 mm, while the lowest was in 2016, with only 574 mm. Overall, the analysis indicates that rainfall in the Pennaiyar basin has been gradually increasing (Fig. 2). Looking at monthly data, October had the highest average rainfall (167.5 mm) and February had the lowest (8.02 mm) (Fig. 3). The period from July to November saw above-average rainfall. However, rainfall decreased during the winter months (January and February) and the pre-monsoon period (March, April and May). These findings align with earlier studies using the Soil Water Assessment Tool (SWAT) model and projected climate data, which also found similar trends in the Pennaiyar river basin (24). A comparison between the monthly average and effective rainfall was also conducted (Fig. 4), which could help estimate the crop WFP for various crops.  $P_{eff}$  was calculated using the USDA Soil Conservation Service (SCS) method, which considers monthly rainfall and estimates the portion that is available for crop use after runoff and deep percolation.

Seasonally, the distribution of rainfall was about 15 % in summer, 43 % during the southwest monsoon, 34 % during the northeast monsoon and 8 % in winter (Fig. 5). Previous reports indicate that the Salem district, part of the Pennaiyar basin, received most of its rainfall during the southwest monsoon (7), consistent with the results of this study. The key crop-growing seasons in the basin, *Kharif* and *Rabi*, align with these 2 monsoon periods. Understanding historical rainfall patterns is essential for managing water resources and planning sustainable agriculture (7, 25, 26).

The spatial and temporal changes in average monthly rainfall across the Pennaiyar basin are shown in Fig. 6. From April to September, the northern region, which is at a higher elevation, received the most rainfall (Fig. 6). Meanwhile, the eastern part of the basin, known as the low-stream command area, got the least rainfall. From October to March, this trend reversed, with the low-

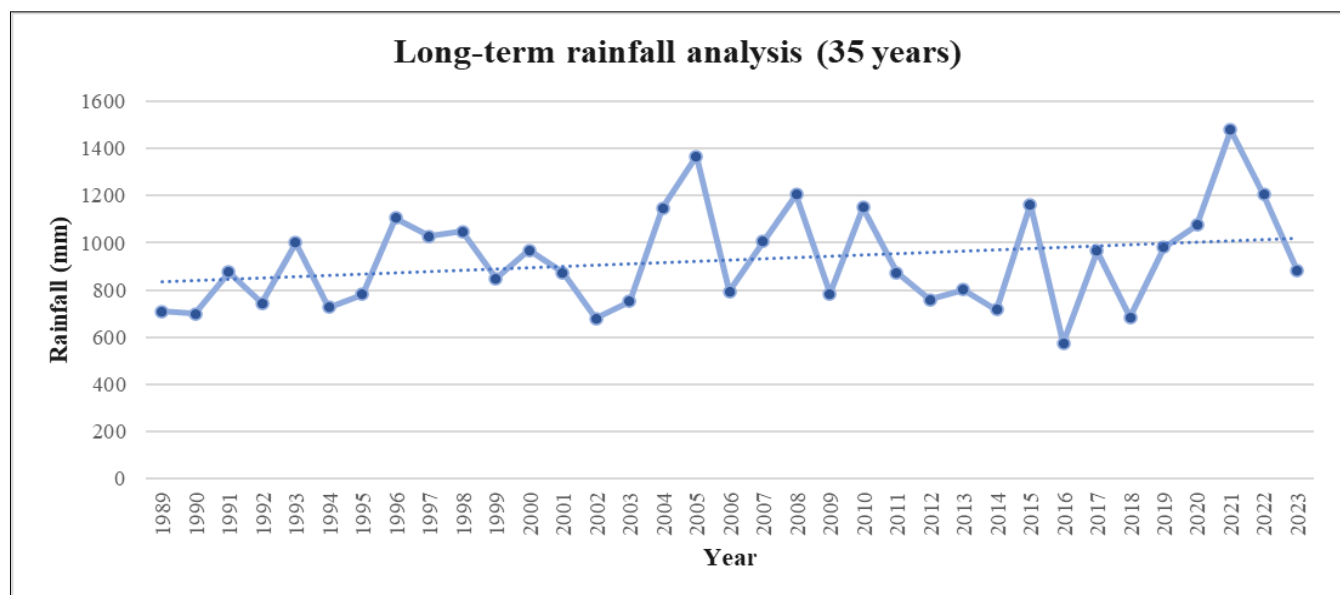


Fig. 2. Annual rainfall pattern (1989 - 2023).

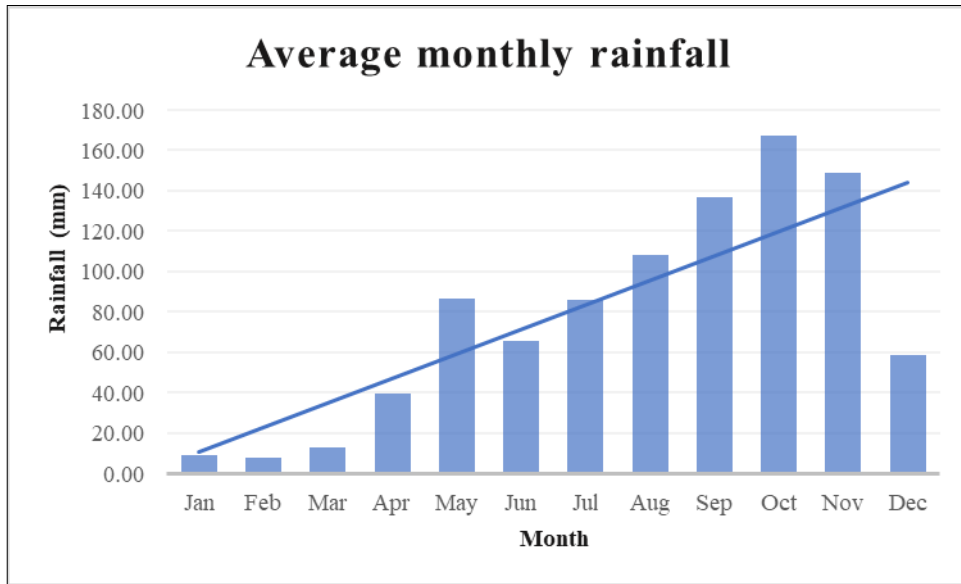


Fig. 3. Average monthly rainfall pattern (1989 - 2023).

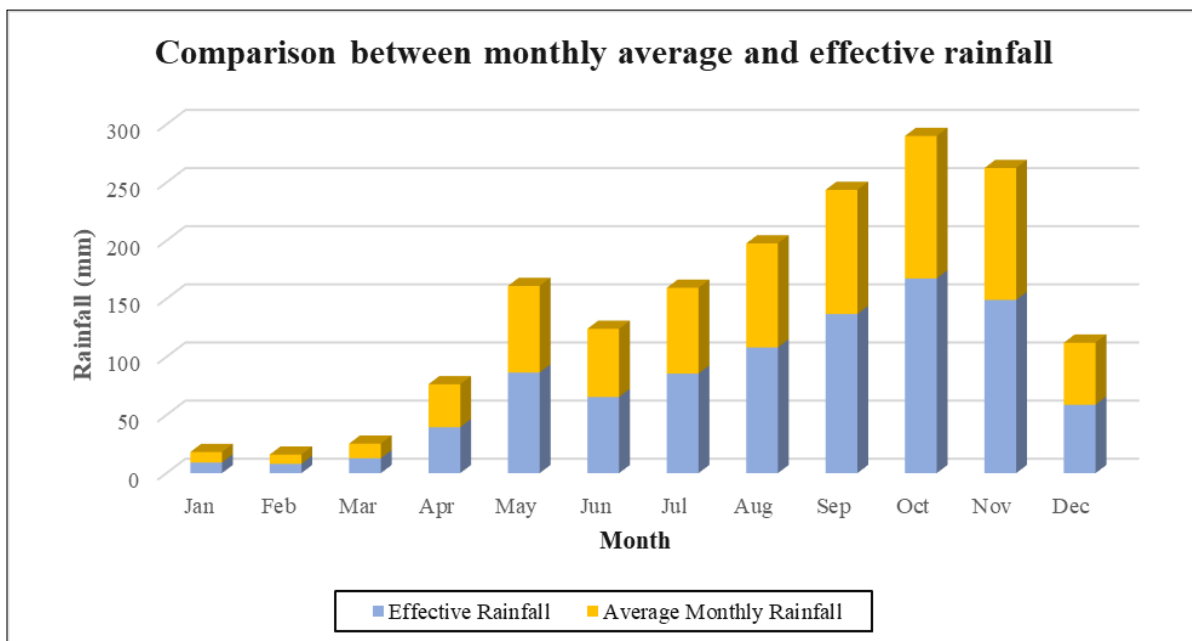


Fig. 4. Comparison between monthly average and effective rainfall (1989 - 2023).

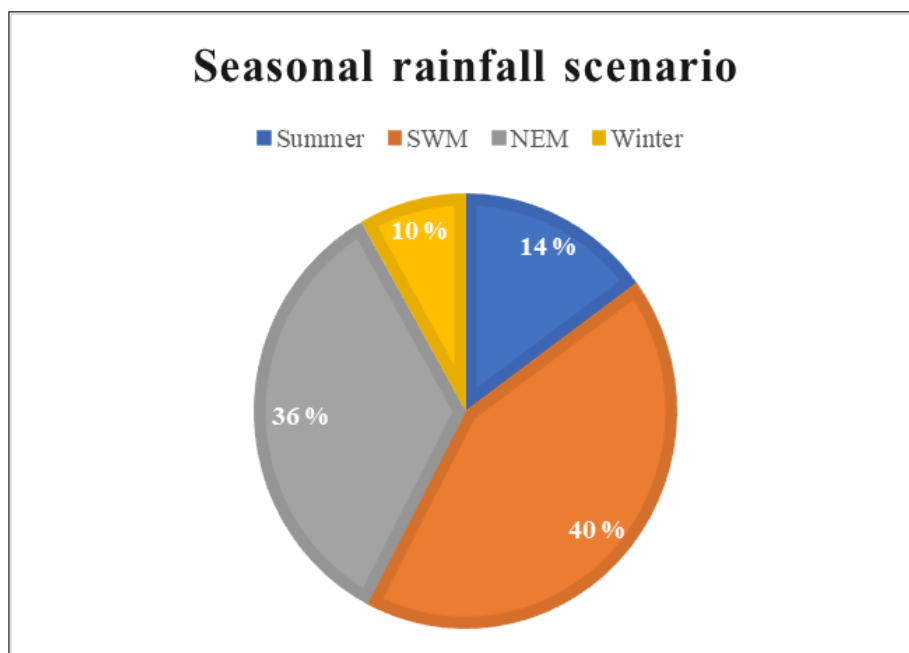
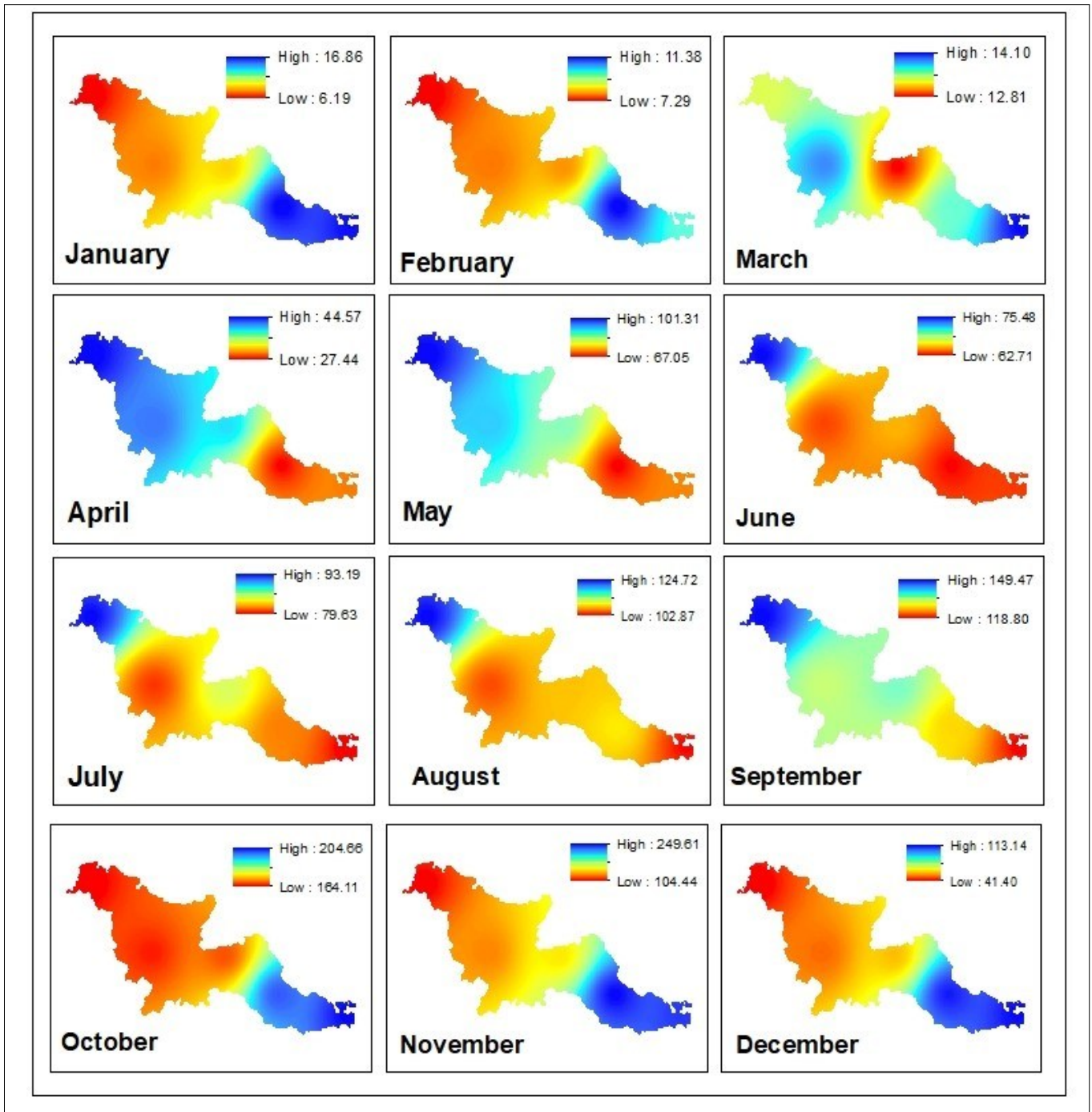


Fig. 5. Seasonal share of rainfall (1989 - 2023).



**Fig. 6.** Spatio-temporal variation of average monthly rainfall (mm) for the Pennaiyar basin.

stream command regions getting more rainfall and the northern areas receiving less. To summarize, the results of erratic monthly rainfall distribution in Pennaiyar basin help in agricultural crop planning and water management planning.

Using the Hargreaves-Samani model, the  $ET_0$  was estimated for the Pennaiyar basin and it was found to vary between 3.5 mm/day and 6.4 mm/day. The temporal variation of monthly average  $ET_0$  is shown in Fig. 7. It is noted that the monthly  $ET_0$  was higher during April, March, May and February. The  $ET_0$  varied from 3.5 mm/day (in December) to 6.4 mm/day (in April).  $ET_0$  is a critical hydro-climatological component for water managers and irrigation planners. The spatio-temporal variation of monthly  $ET_0$  for the Pennaiyar basin is depicted in Fig. 8. High  $ET_0$  was observed in the northern part and lower  $ET_0$  was observed in the downstream command regions of Pennaiyar basin. The crop coefficients for paddy, maize, groundnut and sugarcane are shown in Fig. 9-12

respectively. Using the crop coefficients and  $ET_0$ , crop ET for paddy, maize, groundnut and sugarcane were estimated and noted that the crop ET varied as follows: sugarcane > paddy > groundnut > maize. Similarly, a study reported that the paddy covers 55.04 % of the Pennaiyar river basin of Tamil Nadu and is a high water-consuming crop cultivated dominantly in the head of the river basin, which is cultivated more than half of the gross cropped area and reported sugarcane (27.13 %) is cultivated in nearly half of the area in the middle region of the Pennaiyar river basin (27). Precise assessment of crop ET is the main factor in determining the crop water requirements (28). It helps in agricultural water management and crop cultivation and combat the impact of climate change on water demand. By taking crop ET into account, farmers may optimize water consumption and boost crop yields while contributing to global food security (17, 18).

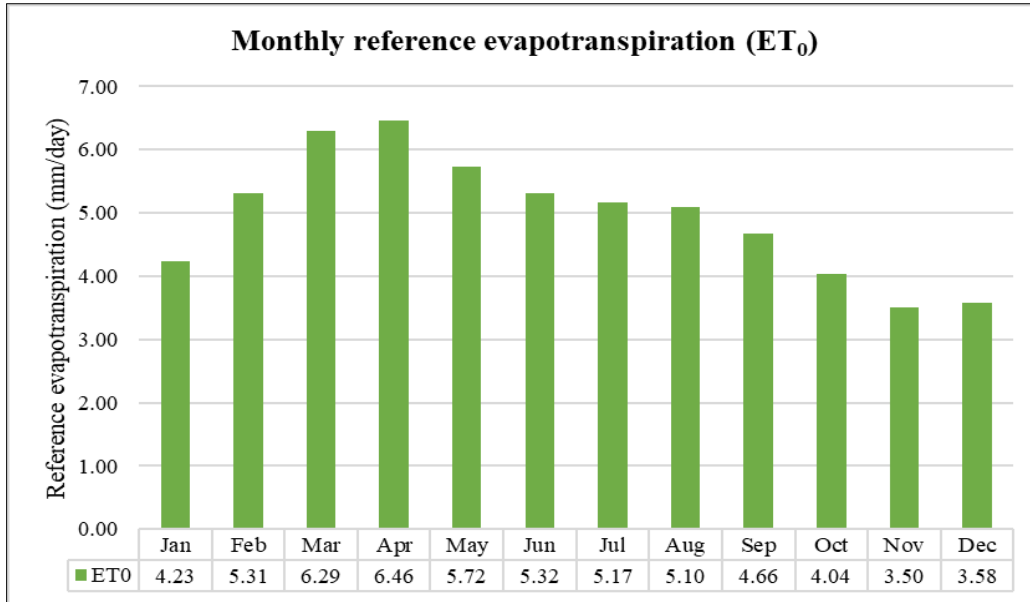


Fig. 7. Monthly reference evapotranspiration (ET<sub>0</sub>) for the Pennaiyar basin.

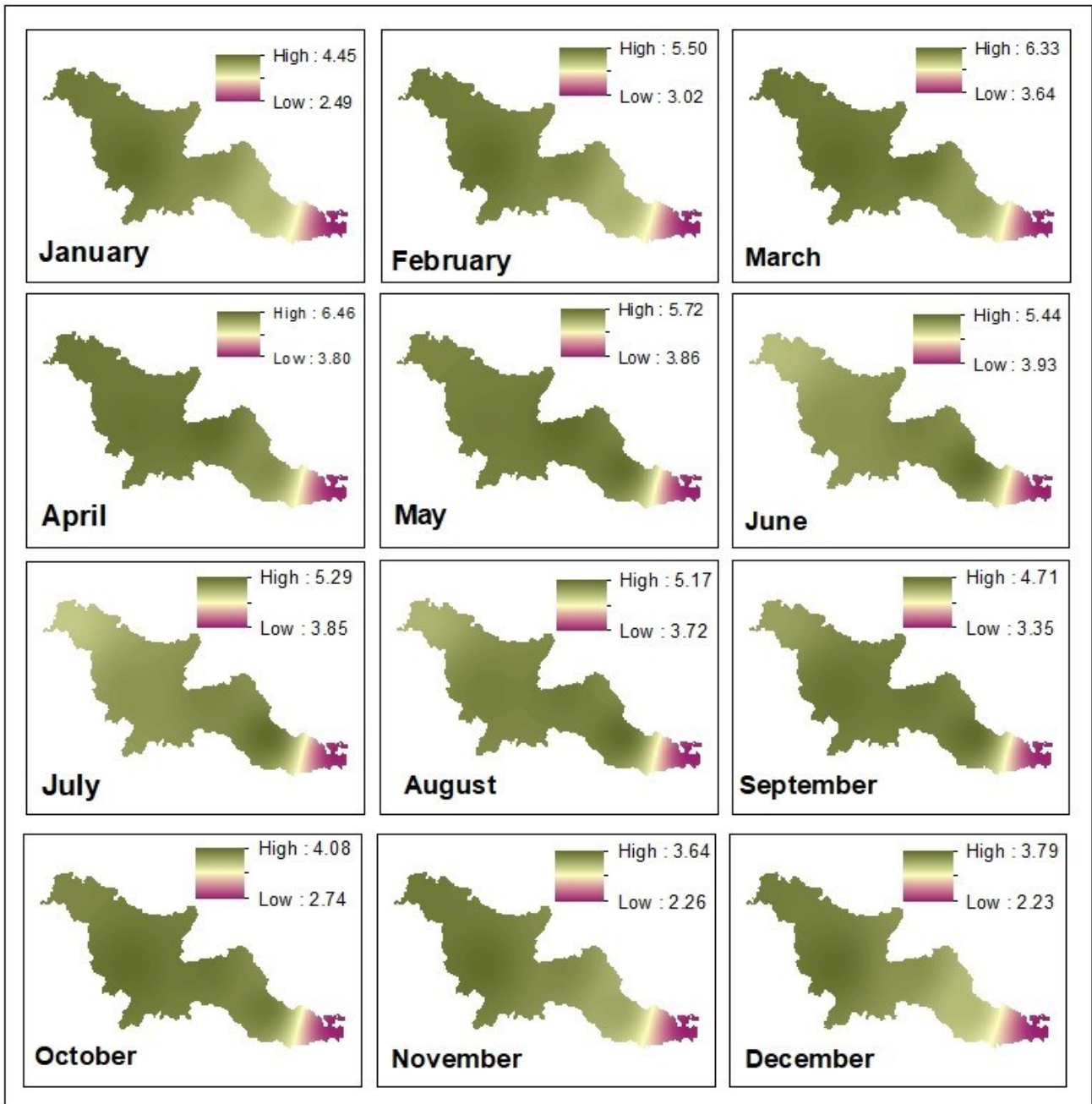
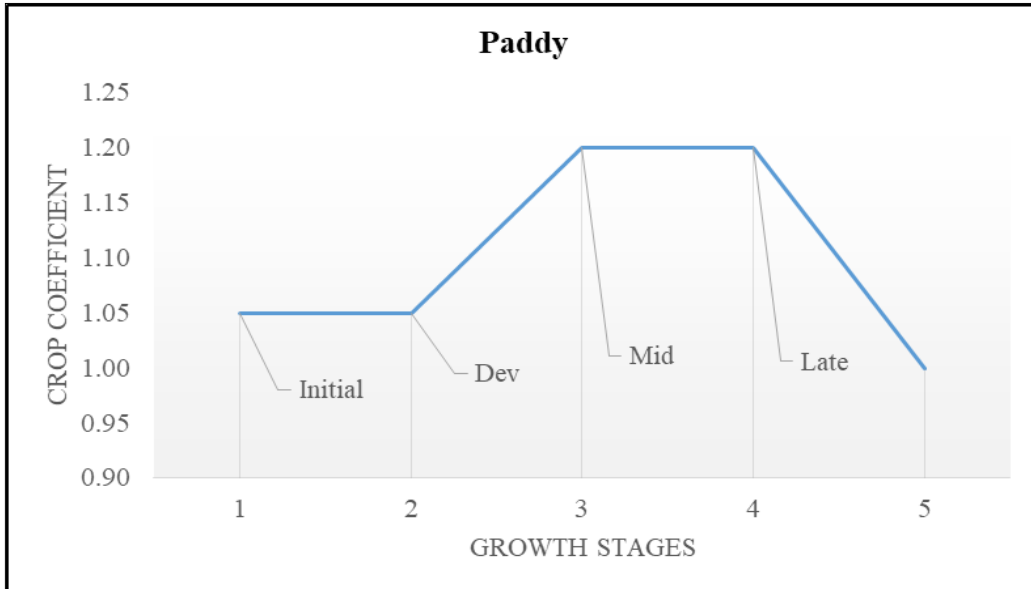
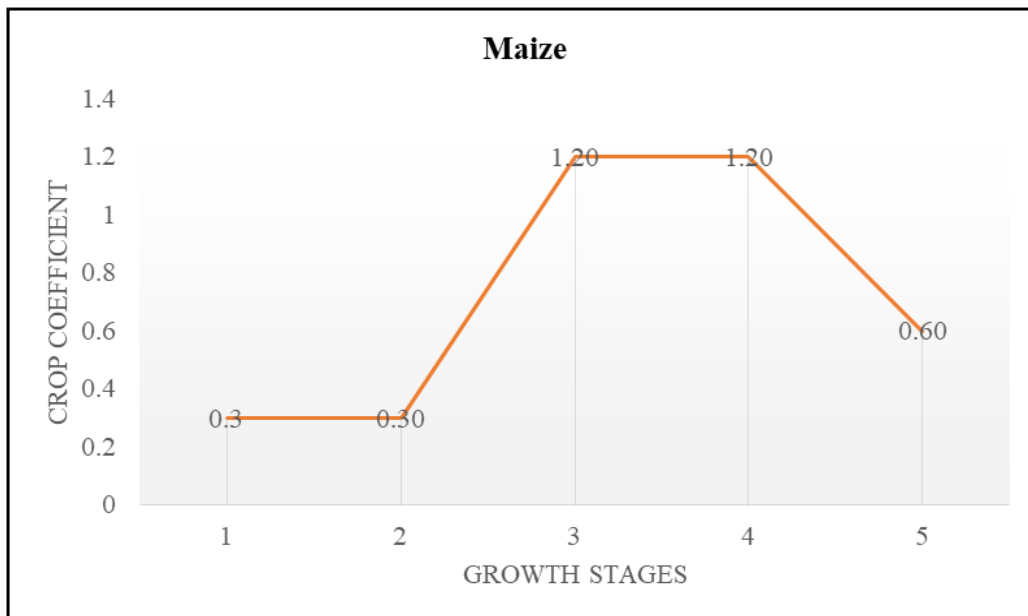


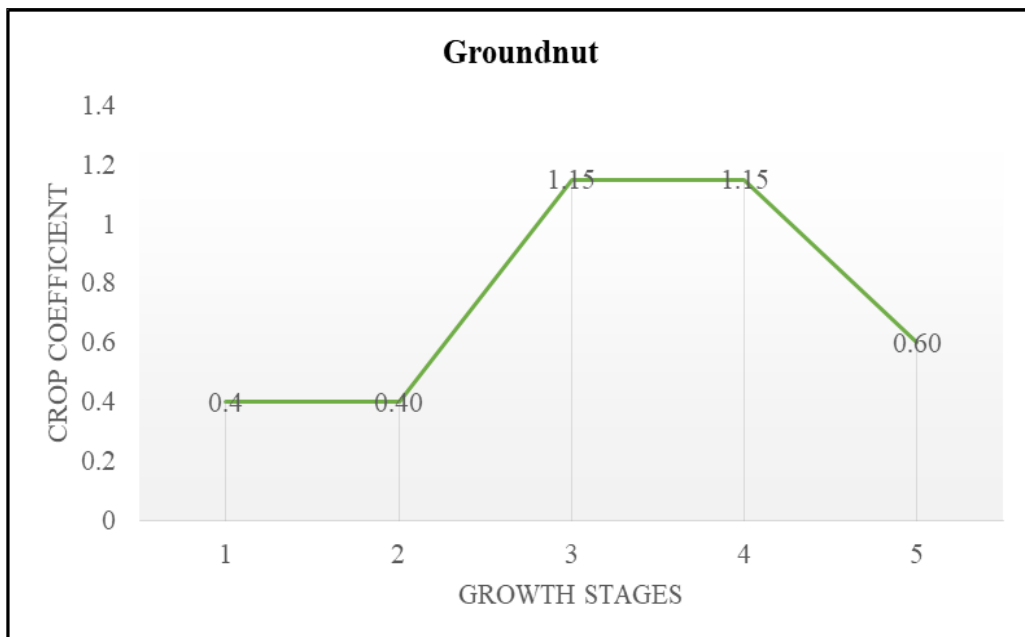
Fig. 8. Spatio-temporal variation of average monthly reference evapotranspiration (ET<sub>0</sub>) (mm/day) for the Pennaiyar basin.



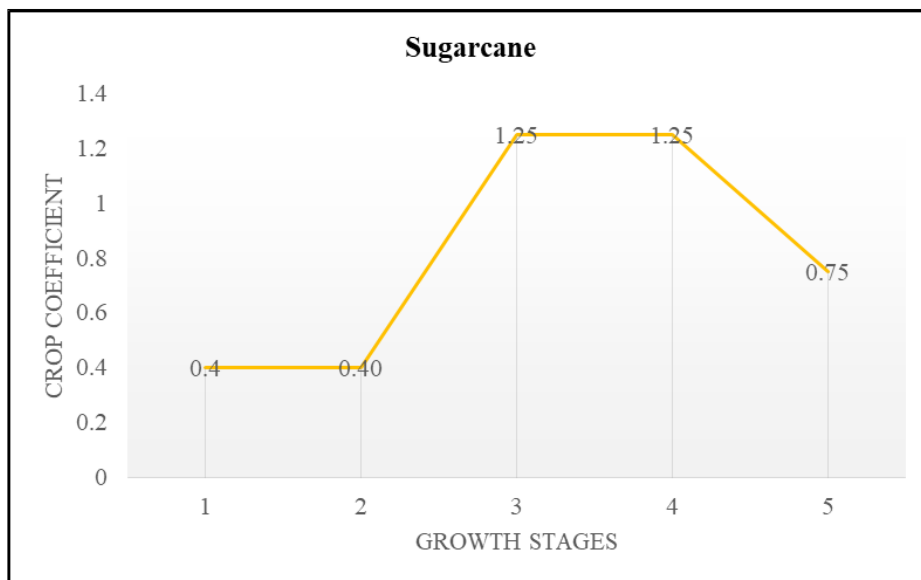
**Fig. 9.** Crop coefficient for paddy.



**Fig. 10.** Crop coefficient for maize.



**Fig. 11.** Crop coefficient for groundnut.



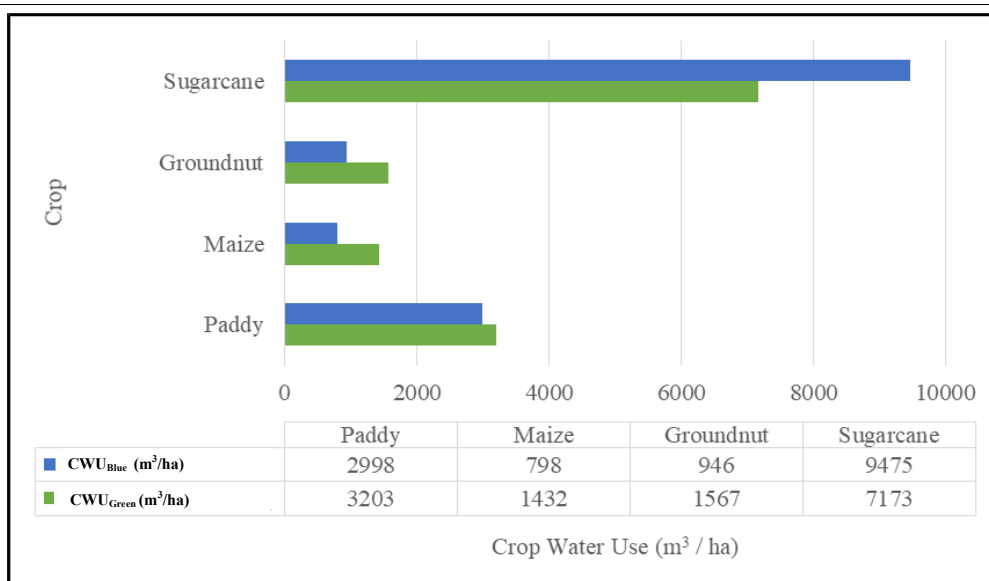
**Fig. 12.** Crop coefficient for sugarcane.

From Table 1, the total WFP for different crops varied as follows: groundnut > paddy > maize > sugarcane. It was noted that the green WFP for paddy, maize, groundnut and sugarcane was 550 m<sup>3</sup>/t, 315 m<sup>3</sup>/t, 951 m<sup>3</sup>/t and 42 m<sup>3</sup>/t respectively. Similarly, the blue WFP for paddy, maize, groundnut and sugarcane was 483 m<sup>3</sup>/t, 181 m<sup>3</sup>/t, 620 m<sup>3</sup>/t and 53 m<sup>3</sup>/t respectively. The blue and green CWU of major crops is shown in Fig. 13. It was found that groundnut and paddy have higher WFPs. It is indicated that current global nut production is affected by different levels of blue water stress in many regions of the world (29). The WFP of sugarcane was found to be less compared to other crops, but the blue water use for sugarcane was higher compared to the green water use.

The following tactics can be used to lessen the WFP without compromising farmers' incomes and yields. Sugarcane's agricultural WFP can be decreased by using the ring pit planting method, irrigation during crucial growth phases, trash mulching and skip furrow irrigation instead of the traditional method. The WFP will be decreased when drip or subsurface drip irrigation is used for sugarcane, but the cost will be high. When it comes to paddy, using a deficit irrigation method rather than full irrigation helps save water while having very little impact on production. To lessen the overall WFP of crops, the irrigation interval suggested in this study may be extended by one day. In paddy, alternate wetting and drying techniques can be used to conserve water, which also lowers greenhouse gas emissions by preserving yields. Reducing the WFP is essential to reducing groundwater overuse and boosting national food security (10, 11).

**Table 1.** Crop water footprint for major crops of Pennaiyar basin

Crop	ET <sub>Green</sub> (mm)	ET <sub>Blue</sub> (mm)	CWU <sub>Green</sub> (m <sup>3</sup> /ha)	CWU <sub>Blue</sub> (m <sup>3</sup> /ha)	WF <sub>Green</sub> (m <sup>3</sup> /t)	WF <sub>Blue</sub> (m <sup>3</sup> /t)	Total WFP (m <sup>3</sup> /t)
<b>Paddy</b>	320	299	3203	2998	533	499	1033
<b>Maize</b>	143	79	1432	798	318	177	495
<b>Groundnut</b>	156	94	1567	946	976	591	1571
<b>Sugarcane</b>	717	947	7173	9475	40	54	95



**Fig. 13.** Blue and green crop water use of major crops.

The categorization of the firkas was done for the Pennaiyar basin as over-exploited, critical, semi-critical and safe. During 2023, it was observed that there were 110 over-exploited firkas, 22 critical firkas, 61 semi-critical firkas and 63 safe firkas. The Dynamic groundwater resource map for the Pennaiyar river basin showed that the northern part of the basin has the majority of over-exploited areas. The district-wise comparison of over-exploited firkas showed that Salem has the highest number of over-exploited firkas (Fig. 14) and Tiruvannamalai district has the highest number of critical, semi-critical and safe firkas (Fig. 15-17). From the above analysis, sustainable groundwater management is essential for addressing water scarcity problems. The optimal extraction of groundwater could be the solution for groundwater depletion, particularly in the overexploited regions of the district. Thus, the policy focus may be tilted towards the water management practices, particularly in the regions of overexploited firka (15, 16).

## Conclusion

Climate change is likely to have a continuous impact on the hydrological cycle parameters. These impacts could be carefully considered in water resources management. A critical and detailed study on the Pennaiyar basin, visualizing various aspects of rainfall analysis, dynamic assessment of groundwater status and estimation of ET and crop WFP for major crops of the Pennaiyar river basin was done. Based on the detailed assessment, sustainable and innovative water management techniques like rainwater harvesting, desalination, greywater recycling, aquifer recharge and water reuse were proposed for the Pennaiyar basin, which is crucial for ensuring sustainable water access and long-term resilience in a changing climate. The results from this study pave the way for a positive impact on rural livelihoods by emphasizing water management and adaptation by the smallholder farmers and achieving water security for crop production in the Pennaiyar basin.

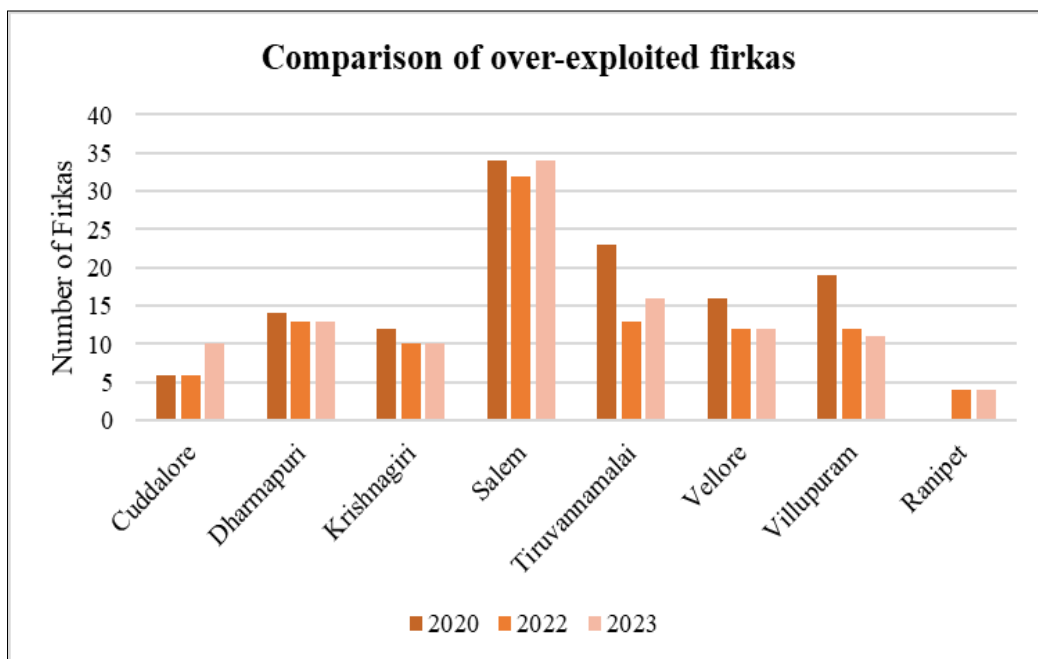


Fig. 14. District-wise comparison of over-exploited firkas.

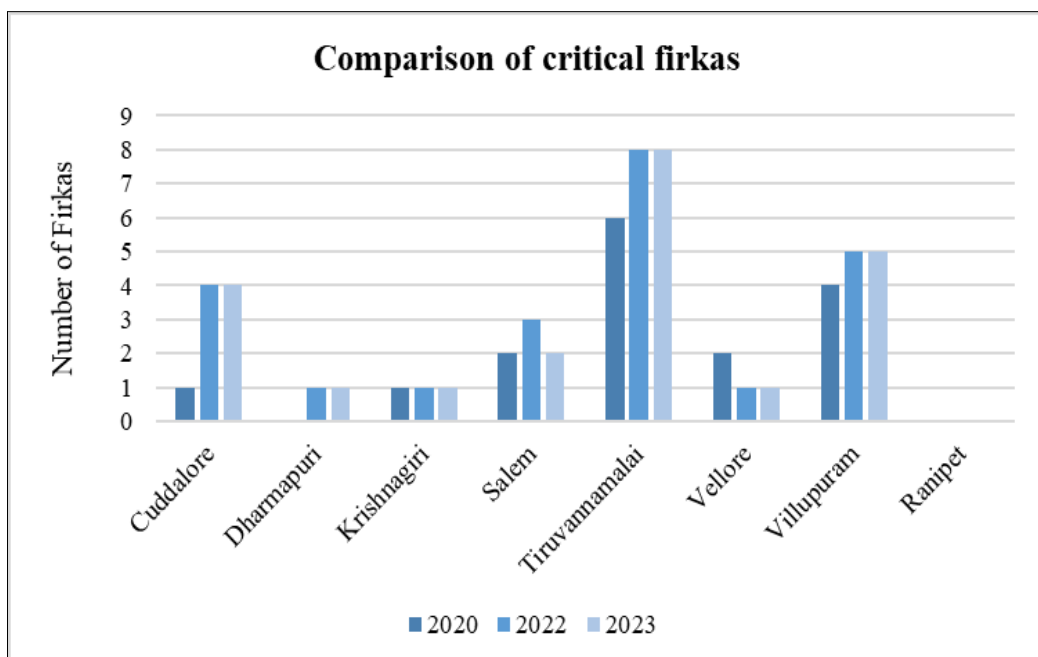


Fig. 15. District-wise comparison of critical firkas.

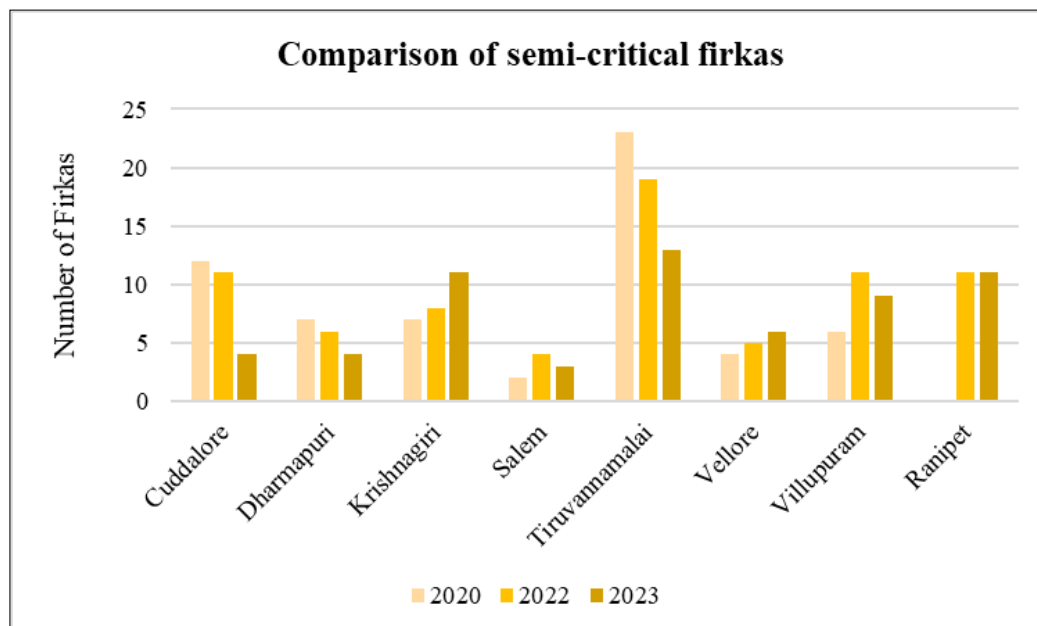


Fig. 16. District-wise comparison of semi-critical firkas.

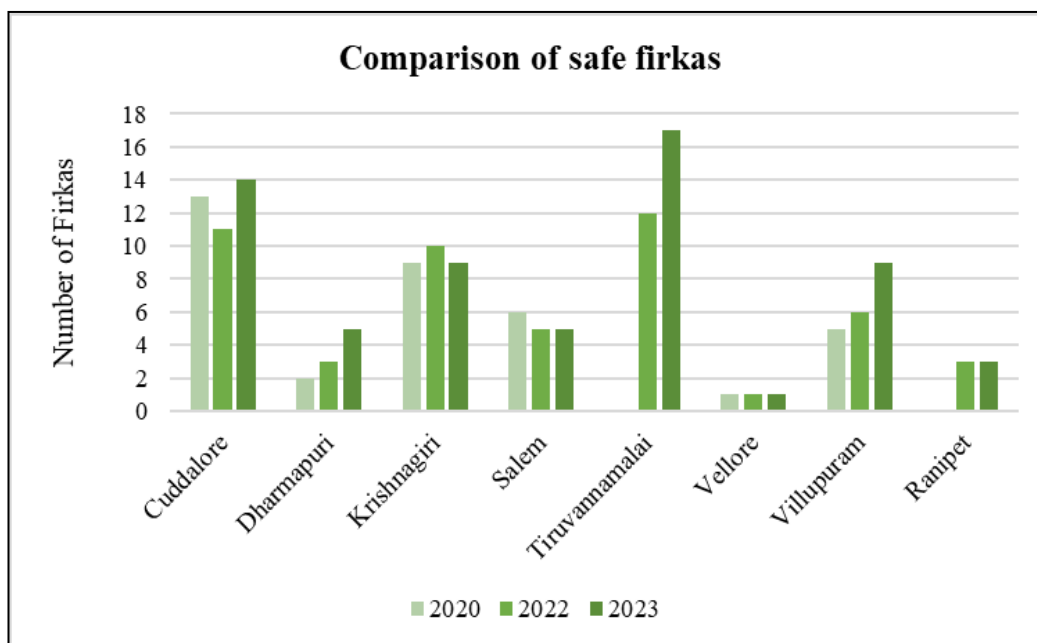


Fig. 17. District-wise comparison of safe firkas.

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## Authors' contributions

ARA was involved in conceptualization and methodology and contributed to writing the original draft, data curation, formal analysis and visualization. RJ participated in methodology development, resource provision, data curation and writing through review and editing. CR supervised the study and contributed to data curation, writing the original draft and review and editing. AV contributed to data curation and manuscript review and editing. MS was involved in reviewing and editing the manuscript. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of Interest:** The authors declare no conflict of interest.

**Ethical Issues:** None

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