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Original Article

Variation and Trends of Irrigation Requirements of Rice Paddies in Korea

Temba Darlington Nkomozepi, Sang-Ok Chung*

Department of Agricultural Civil Engineering, Kyungpook National University, Daegu 702-701, Republic of Korea

Abstract

Understanding the temporal variability of agricultural parameters derived from historical climate data is important for planning in agriculture. Therefore, this study assessed the magnitude and recent trends of the transpiration ratio defined as the crop water use per harvested yield for the period from 1980 to 2010. The crop water use was estimated using the Food and Agriculture Organization's Crop Wat model for eight administrative provinces in Korea. The temporal trends and spatial uncertainty were explored using the Mann-Kendall and Theil Sen's methods. The regional average rice yield was 6.31 t ha^{-1}(range 5.9 to 6.9 t ha^{-1}). The results showed that the rice yield in Korea increased by 26 kg $ha^{-1}yr^{-1}$. Overall, the regional average transpiration ratio was 1,298 m^3 t^{-1} (range 1,162 to 1,470 m^3 t^{-1}). From 1980 to 2010, the transpiration ratio decreased by 8.2 m^3 t^{-1} (range 2.7 to 14.4 m^3 t^{-1}), largely as a result of the increasing yield. The statistical approach to historical data used in this study also provides a basis for simulating the future transpiration ratio.

Keywords : blue water, green water, irrigation, Mann-Kendall, water use efficiency, Korea

Introduction

Independent of their direction, amplitude and pace, year to year climate changes have impacts on agriculture, and more generally, ecosystem functionality and productivity (Büntgen et al. 2012). Understanding the variability of agricultural parameters derived from historical rainfall and temperature data is important in climate variability impact assessment and mitigation (Mair et al. 2013; Lehmann et al. 2013). Thus, the trends of agricultural parameters have been widely studied using observed data, crop models and climate scenarios.

In Korea, 62% of the total water use is allotted to agricultural water, which is mostly utilized for paddy rice (*Oryza Sativa*) irrigation. Paddy rice fields account for about 12% of the land area in Korea and are a major feature of the landscape (Kim et al. 2006). Therefore, the quantification of paddy water use and crop productivity is of interest to agricultural researchers. It follows that any absolute increase in water use is equal to an absolute increase in water depletion that has to be compensated by green (rainfall) and blue (surface or ground water sources) water resources (van Halsema and Vincent 2012). The crop water-use efficiency (WUE) is the inverse of the transpiration ratio (TR), which is defined as the ratio of the evapotranspiration to the harvested yield.

When the TR is partitioned into the green and blue components it can provide an innovative and convenient approach to assessing water resource utilization, taking the crop production and irrigation water source into account (Marta et al. 2012; Sun et al. 2013a). While several studies have already investigated derivatives of the transpiration ratio of paddy rice in Korea, a review of pertinent literature revealed that the impact of climate variability on the TR or WUE has not been investigated. Accordingly, the objective of this paper is to assess the historical trends of irrigation requirements, paddy yield and water use efficiency in Korea.

Materials and Methods

Study area

Korea is located in North East Asia between China and Japan, and is surrounded by the Yellow Sea, South and East Seas, on the west, south and east sides, respectively (33° - 45°N Latitude; 124° - 131°E Longitude). Korea is subdivided into eight administrative provinces, which can be studied independently (Gyeonggi, Gangwon, Chungnam, Chungbuk, Gyeongbuk, Jeonbuk, Jeonam and Gyeongnam) (Figure 1). The Korean climate follows the Asian monsoon with distinct monsoon winds and complex climate characteristics that include continental and oceanic features. The average annual rainfall in Korea is 1,245 mm (ca. 1.4 times the global average). Rice is the main staple crop in Korea. The rice growing period is

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*Corresponding Author: Sang-Ok Chung, Tel. 82-53-950-5734, Fax. 82-53-950-6752, Email. sochung@knu.ac.kr

from May to September, and monoculture is the general practice. About 77% of the paddy fields lie on inceptisol soils. Irrigation water is supplied from May to September to keep the water depth at 5 - 10 cm and the rice is harvested in late October (Chung 2013).

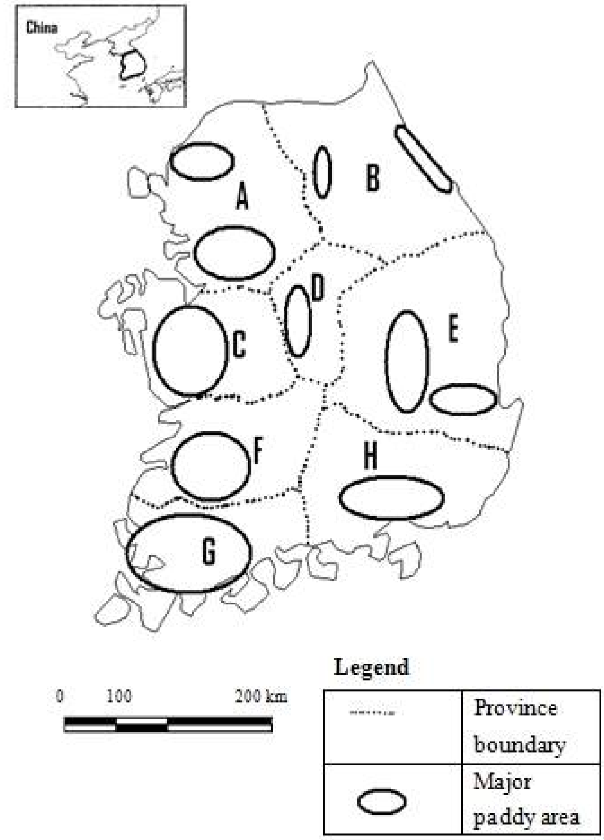

Figure 1. Map of Korea and major rice growing regions marked A to H

Crop water use

The FAO Crop Wat model (Smith 1992) was used to compute the crop water requirement (ET_c), effective rainfall upper limit (R_{eff}) and net irrigation water requirement (NIR) for the 8 provinces covering the entire period from 1980 to 2010. Table 1 shows the parameter values selected for the Crop Wat computations under fully irrigated paddy conditions prevalent in Korea (Chung and Nkomozepi 2012). All provinces were assumed to have adopted the management practices recommended by the Rural Development Administration (RDA). Descriptions of the Crop Watmodel and parameters used therein can be found in Smith (1992). Climate data from 1980 to 2010 including temperature, rainfall, wind speed and relative humidity were collected from the Korean Meteorological Administration (http://kma.go.kr, accessed 4 April, 2013).

The crop water requirement option and the model's default 10-day time step were used to compute the crop water use. Herein, the crop water use (CU) is defined as the water required for evapotranspiration, land preparation and inundation, excluding the conveyance and deep percolation losses over the growing season. The United States Department of Agriculture - Soil Conservation Service (USDA-SCS) method was used to compute the effective rainfall upper limit.

$$R \le 250mm;\ \mathrm{R_{eff}} = \mathrm{R} \cdot (125\text{-}0.2\mathrm{R})/125$$
$$R \ge 250mm;\ \mathrm{R_{eff}} = 125 + 0.1\mathrm{R} \qquad (1)$$

where R is the monthly rainfall and R_{eff} is the monthly effective rainfall upper limit.

Transpiration ratio

The water balance for irrigated lowland or paddy rice (the majority of rice in Korea) is different from that for upland field crops as the former crops are grown under inundated

Table 1. Crop Wat parameters

Parameters	Crop Stage					
	Nursery	LPP[1)]	Initial	Dev.[2)]	Mid-Season	Late Season
Duration (days)	30	5	20	20	40	30
K_c	1.20	1.05	1.10	-	1.20	1.05
Puddling depth (m)	-	0.30	-	-	-	-
Nursery area (%)	5					
Critical depletion	0.20	-	0.20	-	0.20	0.20

[1)]LPP Land preparation and pudding [2)]Dev. Development conditions for most of the season (i.e. in fields with a standing water layer of 10 to 100 mm). A blue water withdrawal is often associated with water scarcity, a high opportunity cost and negative environmental impacts, while green water use is natural and generally has a lower opportunity cost (Sun et al. 2013b). The green (TR_{green}) and blue (TR_{blue}) TRs are given by the following equations:

$$TR_{green} = \frac{CU_{green}}{Y} = \frac{\sum_{i=1}^{n} \min(WD, R_{eff})_i}{Y} \quad (2)$$

$$TR_{blue} = \frac{CU_{blue}}{Y} = \frac{\sum_{i=1}^{n} \max(0, NIR)_i}{Y} \quad (3)$$

where CU_{green} is the crop water use from rainfall, CU_{blue} is the crop water use from irrigation, *WD is* the water demand (includes the ET_c and ponding water requirement), R_{eff} is the effective rainfall upper limit, subscript i is the 10-day time step, NIR is the net irrigation requirement or precipitation deficit ($WD\text{-}R_{eff}$), Y is the yield and n is the total number of time steps.

The yield and areas harvested for each province were obtained from the KOSIS (Korea Statistical Information Service) web portal (http://kosis.kr, accessed 8 May, 2013).

Trend analysis

The temporal trends of the ET_c, NIR, R_{eff}, yield and TR for each province were investigated using the Mann-Kendall test and Sen's robust estimator. Several studies have already detected the presence of temporal trends for various time-series using the non-parametric Mann-Kendall test and Sen's robust estimator (Gocic and Trajkovic 2013; Bartolini et al. 2013; Önöz and Bayazit 2012).

The following equations illustrate the MK test statistic S, and the standardized test statistic Z.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \quad (4)$$

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} +1 \text{ if } (x_j - x_i) > 0 \\ 0 \quad \text{if } (x_j - x_i) = 0 \\ -1 \text{ if } (x_j - x_i) < 0 \end{cases} \quad (5)$$

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p (t_p - 1)(2t_p + 5) \right] \quad (6)$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if\ S < 0 \end{cases} \quad (7)$$

where x_i and x_j are the sequential data values for the time series in the years i and j, n is the length of the time series, t_p is the number of ties for the pth value and q is the number of tied values.

Positive values of S and Z are an indicator of an increasing trend, while negative values indicate a decreasing trend. The magnitude of the test statistic Z determines the statistical significance of a trend. If the calculated Z is less than $Z_{p/2}$, where p represents the p-value (e.g. $Z_{0.025}$ = 1.96), then thenull hypothesis can be rejected, implying that the trend is not statistically significant for the p-value level (Önöz and Bayazit 2012). The Sen's slope estimator is a non-parametric procedure for estimating the slope (a) of the trend in a sample of n pairs of data. If the n values of a_i in Eq. (8) are ranked by magnitude, the Sen's slope estimator is the median slope (a_{med}) computed using the following equations (Gocic and Trajkovic 2013)

$$a_i = \frac{y_j - y_k}{j-k} \text{ for } i = 1, \ldots, n \quad (8)$$

$$a_{med} = \begin{cases} a_{[(n+1)/2]}, & \text{if } n \text{ is odd} \\ \frac{a_{[n/2]} + a_{[(n+2)/2]}}{2}, & \text{if } n \text{ is even} \end{cases} \quad (9)$$

where y_j and y_k are data values at successive times j and k ($j>k$), respectively (Gocic and Trajkovic 2013). A negative or positive a_{med} indicates a downward or upward trend, respectively, while the magnitude of a_{med} gives the steepness.

Furthermore, box plots were used to present the variability pictorially, along with qualitative comparisons.

Results and discussion

In the box and whisker plots herein, the length of each box represents 50% of the respective data distribution (inter-quartile range) and is a measure of the variability. The lines that cut across the boxes represent the respective data means. The length of the error bars denotes the range of the data and is also a measure of the variability.

Crop water use

The variation (uncertainty) of the ET_c, R_{eff} and NIR from 1980 to 2010 is presented in the box and whisker plots in Figure 2, which show a relatively high temporal and spatial variability. Figure 2 also shows that Gyeongbuk province had the highest ET_c and lowest R_{eff} and thereby the highest NIR. When considering the mean alone, the ET_c and R_{eff} exhibited a high spatial variability, which was significantly less for the NIR. This could be attributed to the fact that in the initial stages, a high amount of water is required for land preparation and to inundate the paddy field. The average ET_c, R_{eff} and NIR were 568 mm, 524 mm and 371mm, respectively. The regional average ET_c, R_{eff} and NIR over the period from 1980 to 2010 were 568 mm (range 533 to 648 mm), 524 mm (range 480 to 569 mm) and 371 mm (range 351 to 454 mm), respectively.

Table 2. Average yield and transpiration ratio (TR) of paddy rice in Korea

Province	Area (ha)	Yield (tha^{-1})	TR (m^3 t^{-1})
Gyeonggi	142,642	6.13	1,327
Gangwon	50,484	5.85	1,363
Chungbuk	65,086	6.32	1,257
Chungnam	173,488	6.81	1,165
Jeonbuk	159,057	6.86	1,162
Jeonam	199,548	6.33	1,246
Gyeongbuk	156,200	6.23	1,470
Gyeongnam	122,577	5.97	1,392
Average	133,635	6.31	1,298

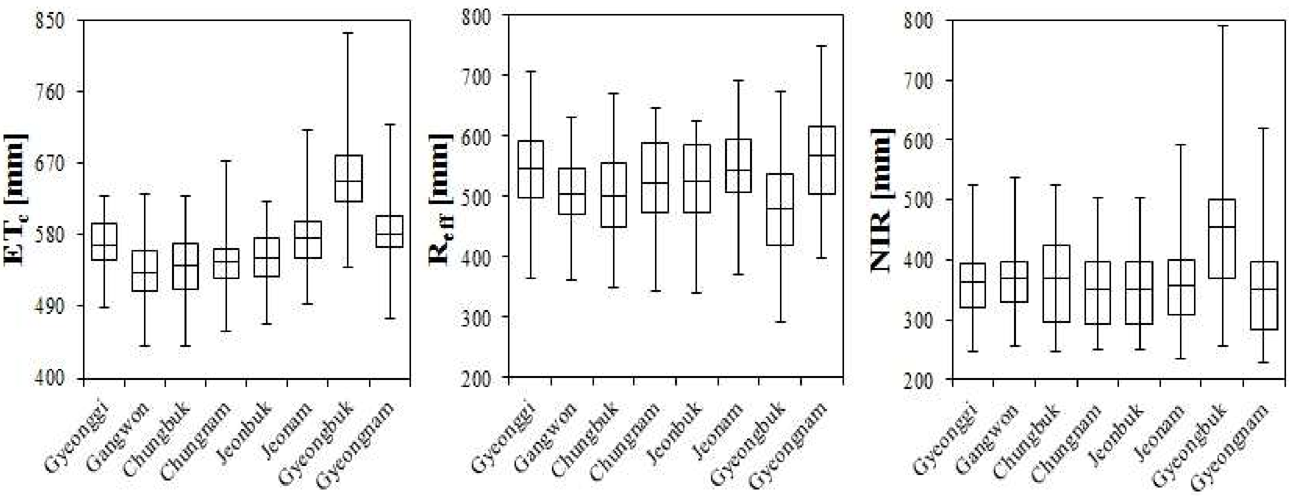

Figure 2. Regional variation of crop ET (ET_c), effective rainfall upper limit (R_{eff}) and net irrigation requirement (NIR) from 1980 to 2010

Transpiration ratio

Figure 3 shows the regional variation of the TR_{blue} and TR_{green} over the period from 1980 to 2010. Gangwon and Gyeongbuk provinces showed the largest variability in the TR. Table 2 shows the area, average yield and TR of paddy rice. The average area under rice was about 134,000 ha per province. Overall, the regional average TR_{blue}, TR_{green} and TR over the period from 1980 to 2010 were 597 m^3 t^{-1} (range 513 to 742 m^3 t^{-1}), 701 m^3 t^{-1}(range 648 to 800 m^3 t^{-1}) and 1,298m^3 t^{-1} (range 1,162 to 1,470 m^3 t^{-1}), respectively. The average paddy rice yield was 6.31 t ha^{-1}(range 5.9 to 6.9 t ha^{-1}).

Trend analysis

The trend analysis statistical tests detected a random and statistically significant variability of the ET_c, R_{eff}, NIR and yield over the study period (Table 3). Statistically significant trends at 1% and 5% significance levels ($p < 0.01$ and $p < 0.05$, respectively) were seen for the paddy yield. The absence of a statistically significant trend for the R_{eff} can be attributed to the high uncertainty in rainfall.

The paddy yield in Korea showed a strong increasing trend of about 27 kg ha^{-1} yr^{-1}. Such increases in yield can be attributed to a moderate increase in temperature, decrease in the relative humidity and improvement in technology and farmer management practices (OECD 1999). The eastern provinces

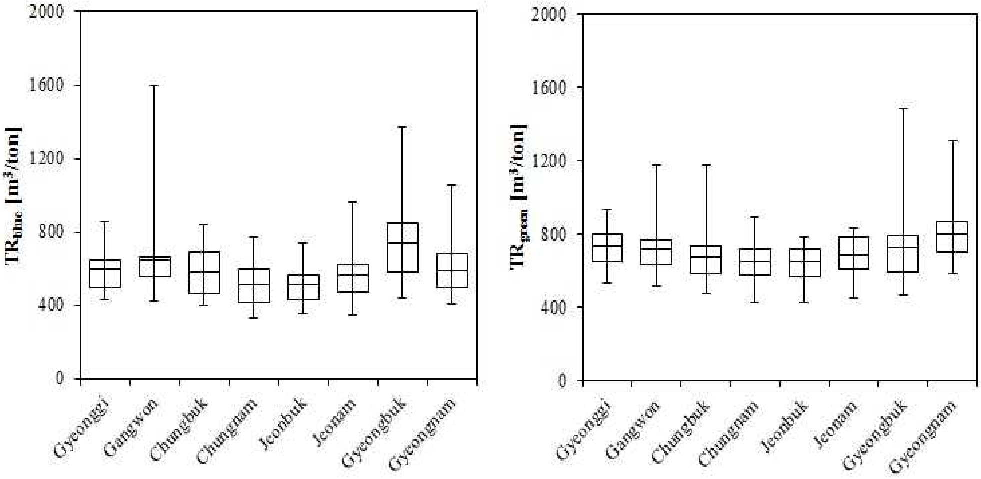

Figure 3. Regional variation of blue (TR_{blue}) and green (TR_{green}) transpiration ratio from 1980 to 2010

Table 3. Summary of Mann-Kendall statistic (S) and Sen's slope (a_{med}) for Crop Wat outputs and yield

Province	S				amed			
	ET_c	R_{eff}	NIR	Yield	ET_c mm yr^{-1}	R_{eff} mm yr^{-1}	NIRmm yr^{-1}	Yield kg yr^{-1}
Gyeonggi	-33	131	-83	215^{**}	-0.5	3.3	-1.9	29^{**}
Gangwon	107	3	61	244^{**}	1.2	0.2	1.3	39^{**}
Chungbuk	-33	11	-21	152^{**}	-0.6	0.2	-0.6	21^{**}
Chungnam	-39	11	-11	183^{**}	-0.4	0.5	-0.3	27^{**}
Jeonbuk	125*	3	45	99	1.4*	0.2	1.4	13
Jeongnam	28	51	-41	43	0.4	1.7	-1.3	7
Gyeongbuk	-47	3	-19	226^{**}	-0.8	0.0	-0.6	34^{**}
Gyeongnam	-45	23	-31	228^{**}	-0.7	0.9	-0.8	37^{**}
All	63	236	-100	1390^{**}	0.1	0.90	-0.4	27^{**}

$^{*}P < 0.05$, $^{**}P < 0.01$

showed the greatest increases in yield. Overall, the trends for the ET_c and R_{eff} were computed to be positive, while those for the NIR were negative over the study period, although the majority were not statistically significant. Plus, since the null hypothesis could not be rejected, no trends were detected for the ET_c, R_{eff} and NIR in Korea over the period from 1980 to 2010. Trends are most likely to be detected when assessing over a longer period with more location specific rainfall data. Thus, the fact that the trends of the ET_c and R_{eff} were not significant over 30 years underscores the notion of modest climate change as opposed to the rapid, significant and dangerous climate changes currently prevalent in literature.

Table 4 shows the summary of the MK statistic (S) and Sen's slope (a_{med}) for the TR. This table summarizes the trends of the TR_{blue} and TR_{green} and total TR. When the data were assessed, only a handful of the TR_{green} and TR_{Blue} were statistically significant (α = 0.05). Yet, despite the statistical insignificance of the TR_{blue} and TR_{green} trends, the S statistic showed that the decreasing trend for the TR_{blue} substantially exceeded that for the TR_{green}, which is advantageous in agricultural systems due to the reduced cost associated with drawing irrigation water. Ideally, crop planting dates and the best management practices should be employed to utilize as much rainfall (TR_{green}) as possible in crop production in order to minimize the TR_{blue} (Sun et al. 2013b). Jeonbuk province showed the least decreasing trend for the TR, while Gyeongbuk province showed the greatest.

Table 4. Summary of Mann-Kendall statistic (S) and Sen's slope (a_{med}) for TR

Province	S			a_{med} (m^3t^{-1})		
	TR_{blue}	TR_{green}	TR_{total}	TR_{blue}	TR_{green}	TR_{total}
Gyeonggi	-155^{**}	-53	-241^{**}	-6.5^{**}	-1.4	-9.3^{**}
Gangwon	-49	-147^{**}	-201^{**}	-1.8	-5.1^{**}	-8.1^{**}
Chungbuk	-101	-79	-229^{**}	-4.4	-3.5	-7.2^{**}
Chungnam	-67	-105	-211^{**}	-2.7	-4.2^{*}	-7.5^{**}
Jeonbuk	-1	-9	-125^{*}	-0.0	-0.2	-2.7^{*}
Jeongnam	-91	-7	-137^{*}	-3.4	-3.5	-5.8^{*}
Gyeongbuk	-115*	-99	-287^{**}	-7.6^{*}	-5.3	-14.4^{**}
Gyeongnam	-129	-125	-311^{**}	-5.6	-5.2	-12.0^{**}
All	-708	-624	-1742^{**}	-4.1	-3.1	-8.2^{**}

*, P<0.05, **, P<0.01

This can be attributed to the fact that Jeonbuk and Jeonam provinces did not report such statistically significant yields as the other provinces.

The TR showed a statistically significant decreasing trend in all provinces. Spatially, the greatest decreasing trend was observed in the southeastern parts of the country, while the smallest decreases were observed in the southwest. The decreasing trends in the northern provinces were close to the national average at about 8.2 m^3 t^{-1}. While a negative a_{med} depicts a decreasing trend for the transpiration ratio, a positive a_{med} depicts an increasing trend of water use efficiency.

Aside from the results of this study being descriptive and procedural knowledge, they are also of great utility in agriculture and climate variability studies. The transpiration ratio approach can be used to address the multifaceted nature of challenges in the agricultural environment. The non-parametric statistical tests used herein represent a way to overcome the challenges of analyzing climate and water resources data, which are of a stochastic nature. The results herein also differ from previously published studies due to the longer time series (30 years) and fundamental differences in the approaches to the transpiration ratio. The TR_{green} and TR_{blue} determined in this study are greater than those reported in other research (Chapagain and Hoekstra 2010 Yoo et al. 2013b). This difference is a result of the time step of the analysis of the water balance, which was 10 days in this study, yet only 1 or 5 days in other studies. Meanwhile, in contrast to the results of Sun et al. (2013b), the trends of the R_{eff} and ET_c herein were most not statistically significant and the yield increased over the study period. Therefore, this proves the utility of this study in that the variability and trends of the crop water use and transpiration ratio varied according to the study area and period. This study was only made possible by the recent public availability in Korea of climate, yield and long term time-series data fort he last 30 years. Global climate change has been predicted to impact the magnitude of the irrigation water demand, making it paramount to investigate the transpiration ratio in the future (Chung and Nkomozepi 2012; Chung et al. 2011). Thus, the statistical approach to historical data used in this study provides a basis for future simulations and will be applicable to other regions of interest.

Conclusion

The historical spatial and temporal variability of the transpiration ratio in Korea were explored statistically using simulations of the net irrigation water requirement (NIR) and observations of climate and yield. The regional average ET_c, R_{eff}, NIR and yield over the period from 1980 to 2010 were 568 mm (533 to 648 mm), 524 mm (range 480 to 569 mm), 371 mm (range 351 to 454 mm) and 6.3 t ha^{-1}(range 5.9 to 6.9 t ha^{-1}), respectively. Generally, no statistically significant temporal trends were observed for the crop water requirement, effective rainfall or net irrigation requirement over the study period. Temporally, the greatest decreasing trend in the TR was observed for the south-eastern parts of the country, while the least decreases were observed for the south-west. The decrease in the TR can be attributed to the increasing trend in the yield, which was significantly greater in the eastern provinces. Overall, this study showed that the total transpiration ratio of paddy rice decreased over the last 3 decades (1980-2010) as a result of desirable changes in climate and agricultural management practices, including mechanization.

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