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Research Article

Spatiotemporal Characteristics of Winter Wheat Waterlogging in the Middle and Lower Reaches of the Yangtze River, China

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The waterlogging is a serious agrometeorological disaster caused by excessive soil water during crop growth stages. The middle and lower reaches of the Yangtze River are one of the major winter wheat growing regions in China and at the same time they are waterlogging-prone due to their specific climatic conditions. In this study, we integrated a set of tools to analyze the spatiotemporal features of winter wheat waterlogging in this region. We proposed a waterlogging precipitation index (WPI) based on winter wheat yield loss rate and precipitation anomaly percentage and analyzed the frequency, scope, and intensity of winter wheat waterlogging. The results showed that the spring rainfall had a direct and significant effect on winter wheat yield, and the meteorological yield of winter wheat was negatively correlated with precipitation abnormal event from jointing to maturity stages (March to May) across the whole study area. The matching between the waterlogging severity identified by the WPI and historical winter wheat waterlogging records was relatively high. We also discussed the influences of the other nonmeteorological factors, for example, soil texture, topographic and geomorphic conditions, and local disaster-resisting ability, on the extent of waterlogging damage.

1. Introduction

The agricultural waterlogging is a kind of agrometeorological disaster caused by excessive soil water, which occurs over vast regions worldwide [1] and adversely affects about 10% of the global land area [2]. From the plant physiology point of view, the damage of waterlogging to crops could largely be attributed to the restricted aerobic respiration in roots [3–5], decreased stomatal conductance and leaf water potentials [6], enhanced root and leaf senescence [7], and deficiencies of energy, carbohydrate, and nutrient [8]. As a result of waterlogging, the crop growth and grain yield are usually suppressed [9, 10].

The middle and lower reaches of Yangtze River are a major winter wheat growing area and is also the most serious waterlogging affected area in China, especially during the period from March to May (corresponding to the jointing to maturity stages of winter wheat) [11]. The prevailing waterlogging in this region was mainly caused by the monsoon climate and, partially, the rotated rice-wheat cropping system, which causes the subsoil compact to accommodate flooding rice farming [12]. The agricultural statistical data of Jiangsu and Anhui, two provinces in the middle and lower reaches of the Yangtze River, showed that about 70% meteorological disasters in recent years were waterlogging in Jiangsu [13], while, for Anhui Province, winter wheat

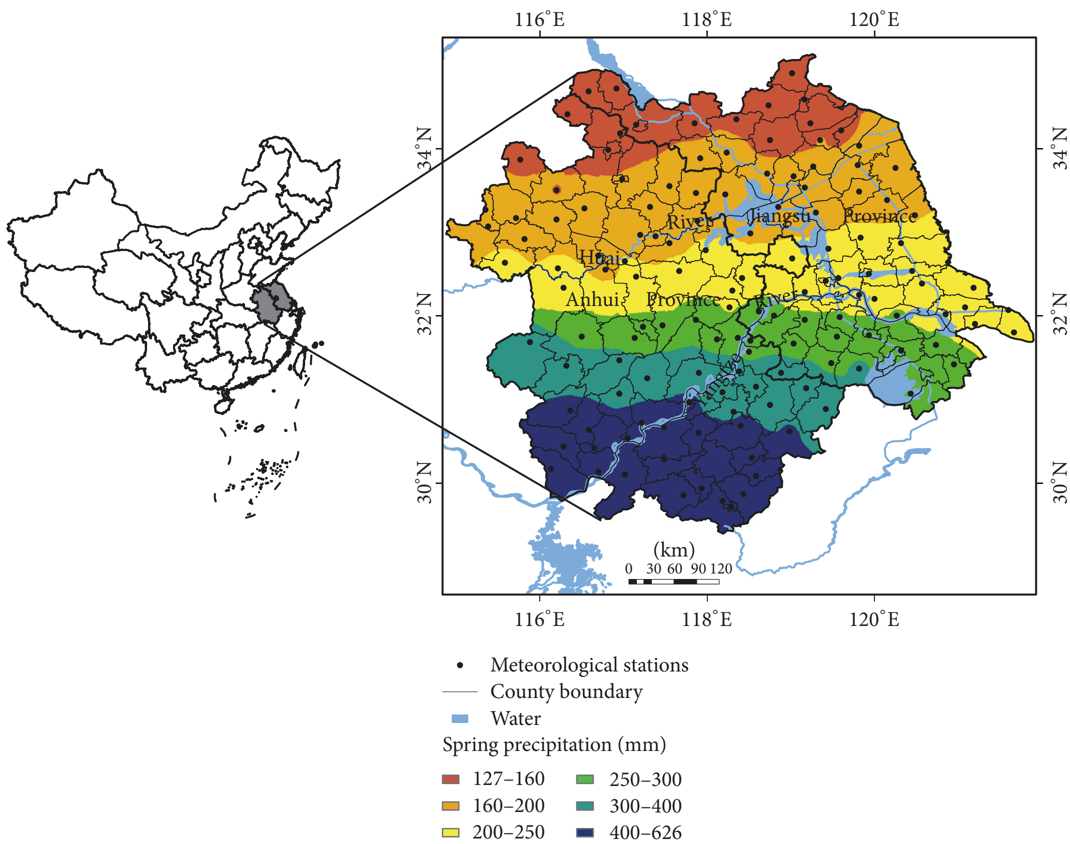

Figure 1: Map of the study area.

waterlogging occurred about every 2.5 years from 1981 to 2005 and caused about 10% yield loss. In severe waterlogging years, for example, 1985, 1991, 1998, and 2003, more than 20% winter wheat yield losses were observed in Anhui Province [14, 15].

Current works about winter wheat waterlogging mainly focused on symptom identification, biochemical mechanism, variety screening, and genetic improvement at laboratory level [1, 16–18]. However, the spatiotemporal characteristic of crop waterlogging is a crucial step in evaluating the influence of waterlogging at regional scale. The waterlogging frequency had close relationship with the spatiotemporal characteristics of precipitation [19–22]. The precipitation anomaly percentage index (PAPI) was commonly used to quantify the intensity and spatial extent of waterlogging [23–25]. The PAPI can be used to effectively assess dry and wet conditions at various temporal scales (e.g., annual, seasonal, and monthly) when applied in a specific region [26]. But PAPI heavily depends on the average values of precipitation, and it has been reported that PAPI might give biased results when applied in large areas with varied climate conditions [24].

The loss of crop yield caused by waterlogging is the compound effects of land surface properties (e.g., topography and geomorphology, soil, and hydrology factors), climate variables (e.g., precipitation), and the stress resistance of certain crop (e.g., winter wheat). The specific physiological characteristics of the target crop further complicate the monitoring of waterlogging in the field. In this study, we purposely omitted the waterlogging formative environment and the impact of waterlogging on crop growth, while proposing a statistical index to evaluate winter wheat waterlogging from the meteorological point of view.

The objective of this study was to characterize the spatiotemporal features of winter wheat waterlogging in the middle and lower reaches of the Yangtze River, China. For this purpose, we analyzed the relationship of meteorological yield and precipitation anomaly percentage during the stem elongation to maturity stages of winter wheat (March to May) and proposed the waterlogging precipitation index (WPI) to identify the severity of winter wheat waterlogging. We further investigated the waterlogging frequency of winter wheat, including its spatiotemporal variations during the period of 1971–2010.

2. Data and Method

2.1. Study Area. The study area is Anhui and Jiangsu Provinces, with an area of about 247,300 km^2 in the middle and lower reaches of the Yangtze River (29°41′–35°20′N and 114°54′–121°57′E) (Figure 1). This area is dominated by alluvial plains, depressions, and lakes, while its south and southwest areas are mainly of hilly and mountainous terrain. This region lies between the south-north climate transition zone in China, with warm temperate zone in the north and subtropical in the south. The annual mean temperature

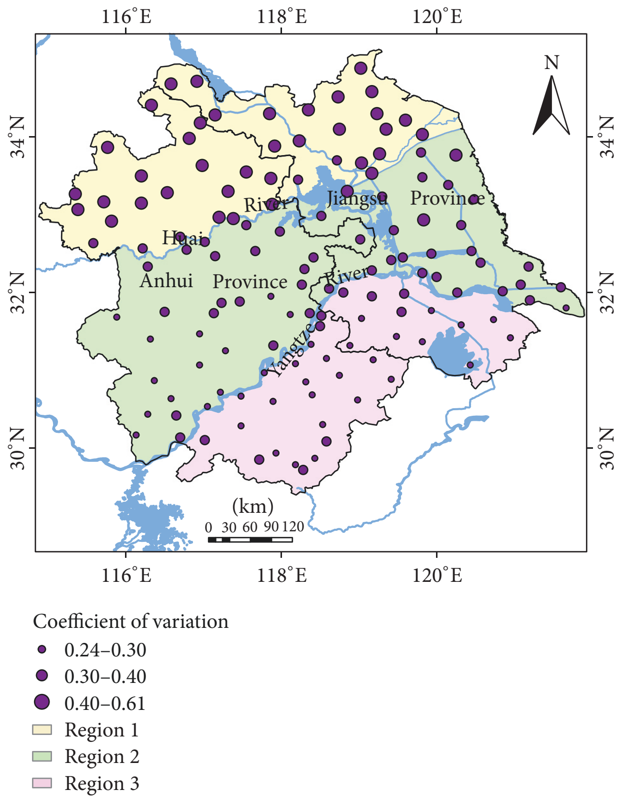

FIGURE 2: Spatial distribution of the coefficient of variation of spring precipitation from 1971 to 2010.

ranges from 13°C to 18°C. The annual precipitation is about 700–1,600 mm, and the annual average precipitation in spring is 127–626 mm increased from north to south.

According to the geographic features of Anhui and Jiangsu Provinces, we divided the study area into three regions, that is, north of Huai River (R1), region between Huai and Yangtze Rivers (R2), and south of Yangtze River (R3), and we also calculated the coefficient of variation of spring precipitation, that is, precipitation from March to May using the observed precipitation data of local meteorological stations. The coefficient of variation of precipitation was divided into three categories by using the quantile classification method, and its spatial distribution was shown in Figure 2. The coefficient of variation ranged from 0.24 to 0.61 in the whole area and generally decreased from north to south.

2.2. Data. The daily precipitation data of 136 meteorological stations and historical waterlogging records of five counties during the period of 1971–2010 were provided by local meteorological departments. The historical winter wheat yield data of all counties from 1971 to 2010 were provided by the statistics bureaus of Anhui and Jiangsu Provinces. It is noted that almost each county in the study area has a meteorological station, so the precipitation and winter wheat yield data could be matched at county level. For county without meteorological station, we took the precipitation value at the geometric center of that county as its representative precipitation data, and the spatially distributed precipitation was obtained by using kriging interpolation.

2.3. Method

2.3.1. Yield Loss Sequence of Winter Wheat. The time series crop yield data can generally be decomposed into trend yield (combined results of agricultural technology advancement and agriculture investment), climate fluctuant yield, and random errors [27]. The random error could often be neglected as minor and irregular effect on crop yields, so the actual winter wheat yield could be expressed as follows:

$$y = y_t + y_w, \tag{1}$$

where y, y_t, and y_w are the actual, trend, and climate fluctuant yields of winter wheat, respectively.

According to the national meteorological industry standard about winter wheat waterlogging issued by the China meteorological administration [28], the trend yield was calculated by using linear moving average method with a window size of 11 years. The relative meteorological yield of winter wheat (y_r), which was taken as the ratio of climate fluctuant yield to trend yield, was used to represent yield loss. The y_r for the ith year is defined as follows:

$$y_{ri} = \frac{y_{wi}}{y_{ti}} \times 100\%, \tag{2}$$

where y_{ti} and y_{wi} are the trend and climate fluctuant yields of winter wheat for the ith year, respectively. According to the correspondence between waterlogging grades and the reference values of crop yield loss rates reported in previous work [28], we further classified y_r into three grades, that is, no loss ($y_r \geq -5\%$), mild loss ($-10\% < y_r \leq -5\%$), and moderate-to-severe loss ($y_r \leq -10\%$).

2.3.2. Precipitation Anomaly Percentage. The precipitation anomaly percentage (PAP) is estimated by using the precipitation (P_i) at a certain period (e.g., annual, seasonal, and monthly) and the mean precipitation ($\overline{P}$, at least over 30-year records) of a specific geographic location and is calculated as follows:

$$\text{PAP} = \frac{P_i - \overline{P}}{\overline{P}} \times 100\%. \tag{3}$$

According to the definition of PAP, the positive, negative, and near zero values of PAP indicate wet, dry, and normal condition for a specific location, respectively. In this study, the spring PAP is labeled as SPAP (Spring PAP), while the positive spring PAP is labeled as PSPAP (Positive SPAP).

2.3.3. Waterlogging Precipitation Index of Winter Wheat. We first analyzed the relationships between the relative meteorological yield and PAP during different growth stages of winter wheat; then we focused on the growth stage of winter wheat with the most sensitive correlation with waterlogging for further analysis.

The meteorological waterlogging can be evaluated by PAPI, and PAPI can effectively evaluate wet conditions relative to the normal years at various temporal scales. For instance, the PAPI would label a region with mild waterlogging if its seasonal precipitation is 25% to 50% more than the normal years [29]. However, the correspondence between waterlogging and precipitation should be varied according to the specific climatic region and crops. So, the PAPI might overestimate the frequency and intensity of waterlogging in areas with relative less precipitation, while underestimate in areas with abundant precipitation. In this study, we proposed a waterlogging precipitation index (WPI) to evaluate the winter wheat waterlogging severity based on yield loss rate and PAP. Taking spring precipitation as an example, the WPI was calculated as the following procedures.

(a) Divide the study area into six subregions by the average total precipitation in spring, that is, <160, 160–200, 200–250, 250–300, 300–400, and ⩾400 mm, using the Jenks natural breaks classification method. The Jenks natural breaks classification method is a data classification method, which seeks to reduce the variance within classes and maximize the variance between classes [30]. The final classification thresholds (i.e., 160, 200, 250, 300, and 400 mm) were the rounding results of the natural breaks classification thresholds. The spatially distributed spring precipitation obtained by using kriging interpolation was shown in Figure 1. It can be found that the spring precipitation in the study area had obvious latitudinal distribution characteristics.

(b) For each meteorological station, select the years when SPAP was greater than 5%, and then calculate the corresponding average winter wheat yield loss rate (Y_r) and average planting area (A), and calculate the corresponding average SPAP for the two yield loss categories (mild and moderate-to-severe losses), respectively. We excluded the data in 1977 and 2002 for validation purpose (Section 3.2). Records showed that widespread waterlogging occurred in Anhui Province and caused about 30 to 50 percent winter wheat yield loss during mid-March and mid-May in 1977 [31], and another moderate-to-severe waterlogging occurred in the south of the study area during mid-April and mid-May in 2002 [11].

(c) Determine the SPAP thresholds (i.e., WPI) for winter wheat waterlogging as follows:

$$\mathrm{SPAP\_thresholds}_k = \sum_{i=1}^{m} w_i \times \mathrm{SPAP}_{ki}, \quad k = 1, 2, \tag{4}$$

in which k indicates two yield loss categories (i.e., mild and moderate-to-severe losses) or the corresponding waterlogging grades (i.e., mild and moderate-to-severe waterlogging). $\mathrm{SPAP\_thresholds}_k$ is the SPAP threshold for the kth waterlogging grade, SPAP_{ki} is the average SPAP of the ith meteorological station calculated in step (b) for the kth yield loss category, and m is the number of meteorological stations in a specific subregion. The weight of the ith meteorological station, w_i, in a subregion is formulated by three factors, that is, the yield loss rate and planting area of winter wheat in each county and the correlation coefficient of SPAP with yield. It is defined as follows:

$$w_i = \frac{Y'_{ri} \times A'_i \times R'_i}{\sum_{j=1}^{m} Y'_{rj} \times A'_j \times R'_j}, \tag{5}$$

where Y'_{ri}, A'_i, and R'_i are the standardized values of the average yield loss rate (Y_r) and the average planting area (A) of winter wheat in each county obtained in step (b) and the correlation coefficient of SPAP with yield (R) for the ith meteorological station. According to the obtained SPAP_thresholds, the winter wheat waterlogging severity could be classified into three grades, that is, no, mild, and moderate-to-severe waterlogging.

2.3.4. Waterlogging Characteristics. To quantify the spatiotemporal characteristics of winter wheat waterlogging, we adopted the frequency of winter wheat waterlogging and calculated the proportion of waterlogging at meteorological station level.

(1) Waterlogging Frequency. The waterlogging frequency (F) is calculated as follows:

$$F = \frac{n}{N} \times 100\%, \tag{6}$$

where N is the total number of years under study and n is the total number of years when the winter wheat waterlogging occurred (identified by the WPI). The waterlogging frequencies for mild and moderate-to-severe levels were calculated separately.

(2) Proportion of Waterlogging at Meteorological Station Level. The proportion of waterlogging (S_p) at meteorological station level was used to measure the extent of waterlogging occurrence for a specific region. S_p is defined as follows:

$$S_p = \frac{m}{M} \times 100\%, \tag{7}$$

where M is the total meteorological station numbers in a specific region and m is the number of meteorological stations with waterlogging. For a specific region, the larger the S_p value, the larger the extent of the waterlogging occurrence. Referring to the division of drought extent in previous work [32], we further classified the waterlogging at regional scale according to S_p. If $S_p \geq 50\%$, it is classified as the so-called large-scale regional waterlogging; similarly, the regional and local waterlogging correspond to $25\% \leq S_p < 50\%$ and $10\% \leq S_p < 25\%$, respectively. If $S_p < 10\%$, it is classified as no waterlogging.

Table 1: Correlation analysis between the average relative meteorological yield and average PAP during different growth stages of winter wheat in each subregion.

Regions	Whole growth period	Emergence to jointing	Jointing to heading	Heading to maturity	Emergence to heading	Jointing to maturity
Entire study area	−0.56**	−0.17	−0.55**	−0.44**	−0.51**	−0.63**
R1	−0.35*	0.11	−0.44**	−0.25	−0.27*	−0.45**
R2	−0.57**	−0.17	−0.55**	−0.37*	−0.50**	−0.61**
R3	−0.63**	−0.29	−0.47**	−0.45**	−0.54**	−0.66**

∗ represents 0.05 significance level; ∗∗ represents 0.01 significance level.

3. Results

3.1. Relationship between Precipitation and Meteorological Yield of Winter Wheat. Table 1 shows the correlation coefficients between the average relative meteorological yield and the average PAP during different growth stages of winter wheat in each subregion. There were significant negative correlations between PAP and meteorological yield at different growth stages of winter wheat, except the emergence to jointing stages. Generally, the higher precipitation corresponded with the relative lower wheat yield, and vice versa. The most significant correlations could be found between the jointing and maturity stages (from March to May) with a correlation coefficient of −0.63 over the whole study area. For this reason, we specifically focused our analysis in the following sections on this period.

Figure 3 shows the spatial distribution of the correlation coefficients between the relative meteorological yield of winter wheat and PAP in spring during 1971–2010. Most of the meteorological stations (130 out of 136) showed negative correlations, and the correlation coefficients of 98 stations were significant at 0.05 or above levels. It was obvious that the correlation coefficients generally increased from south to north, and we noted that six meteorological stations with positive correlation coefficients had the least precipitation and precipitation days in spring during the study period.

We calculated the average PSPAP at meteorological station level and the corresponding average relative meteorological yield for the typical waterlogging years (i.e., 1973, 1974, 1985, 1987, 1991, 1998, and 2010). Figure 4 shows the relationship between the average PSPAP and annual average spring precipitation for stations with winter wheat yield loss. The average PSPAP asymptotically declined with the increased annual average precipitation in spring and gradually approached a steady level when the annual average precipitation in spring exceeded about 350 mm. In areas with high spring precipitation, the winter wheat waterlogging thresholds were generally low, while the thresholds were relatively high in the areas with less precipitation.

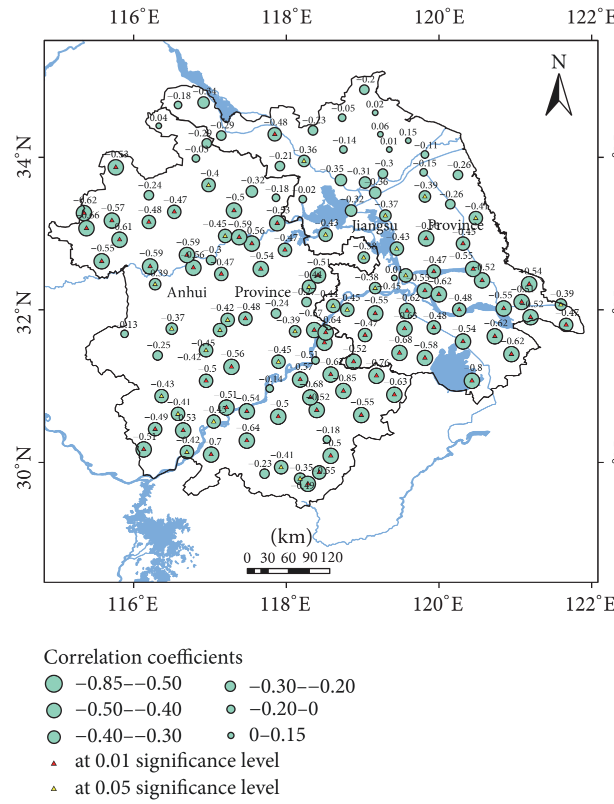

Figure 3: Correlation coefficients between the relative meteorological yield of winter wheat and PAP in spring. The yellow and red filled triangles refer to the correlation coefficients at the 0.05 and 0.01 significance levels, respectively.

3.2. Validation of WPI. The WPI thresholds of winter wheat in the study area were shown in Table 2 according to the calculation procedures in Section 2.3.3. Compared with PAPI, the WPI varies with the average precipitation in spring.

Using the estimated WPI thresholds, we analyzed the spatial distribution of the waterlogging grades for all the meteorological stations in 1977 and 2002, respectively (Figure 5). It showed that most of the meteorological stations suffered from waterlogging in 1977, and the waterlogging in the south of the study area was more serious than the north. In 2002, the moderate-to-severe waterlogging events mainly concentrated in the south of the study area. The spatial patterns of waterlogging in the two typical waterlogging years are generally consistent with previous reports [11, 29].

We further compared the number of years with waterlogging estimated by the WPI and the historical records of waterlogging for five counties (i.e., Guanyun, Huaian, Donghai, Feixi, and Guichi) in the study area (Table 3). The accuracies of winter wheat waterlogging estimated by WPI were between 66.67% and 100% for these five counties.

Table 2: WPI thresholds for winter wheat in the study area.

$\overline{P}_{3-5}$	<160	160–200	200–250	250–300	300–400	>400
SPAP thresholds for mild waterlogging	0.46	0.35	0.32	0.28	0.20	0.19
SPAP thresholds for moderate-to-severe waterlogging	0.7	0.58	0.53	0.40	0.32	0.30

Note. $\overline{P}_{3-5}$ represents average total precipitation in spring.

Table 3: Number of years with waterlogging events in historical records and estimated by the WPI for the five counties in the study area, respectively.

County	Observed (years)	Estimated (years)	Accuracy (%)
Guanyun	4	5	100.00
Huaian	4	5	100.00
Donghai	7	5	66.67
Feixi	7	6	85.71
Guichi	15	11	73.33

3.3. Frequency of Winter Wheat Waterlogging in Spring. We calculated the frequency of spring winter wheat waterlogging for each meteorological station and interpolated using the inverse distance weighted method (Figure 6). It showed that the frequency of waterlogging in spring (Figure 6(a)) ranged between 7.5% and 33%, and the frequencies were above 17% in most of the study area. The maximum frequencies (21–33%) concentrated in the south of the study area and regions along the Huai River in Anhui Province. The areas with spring precipitation below 160 mm were characterized by relatively lower frequencies of waterlogging and the south of Jiangsu Province with spring precipitation ranged between 200 and 300 mm.

The higher frequencies of mild waterlogging (11–18%) were mainly distributed in regions along the Huai River and Yangtze River in Anhui Province and mid-east of the study area (Figure 6(b)). The regions with higher frequencies of moderate-to-severe waterlogging (13–25%) mainly concentrated in the southwest of the study area, while the regions with lower frequencies of moderate-to-severe waterlogging (2.5–9%) were mainly distributed in the east of the study area (Figure 6(c)).

3.4. Interannual Variation of Winter Wheat Waterlogging. Figure 7 shows the annual variations of the proportion of waterlogging in each subregion from 1971 to 2010. The south part of the study area was more vulnerable to waterlogging than the north. The winter wheat waterlogging events in mid-1970s, late 1980s, and the 1990s were more frequent compared with the 2000s. Although R2 and R3 had the same waterlogging occurrence rate, the times were different. For example, R2 had regional waterlogging in 1974, but there was no significant waterlogging in R3. In Supplementary Materials, we interpolated the spring precipitation of each year spatially using the inverse distance weighted method and showed the spatial distribution of winter wheat waterlogging.

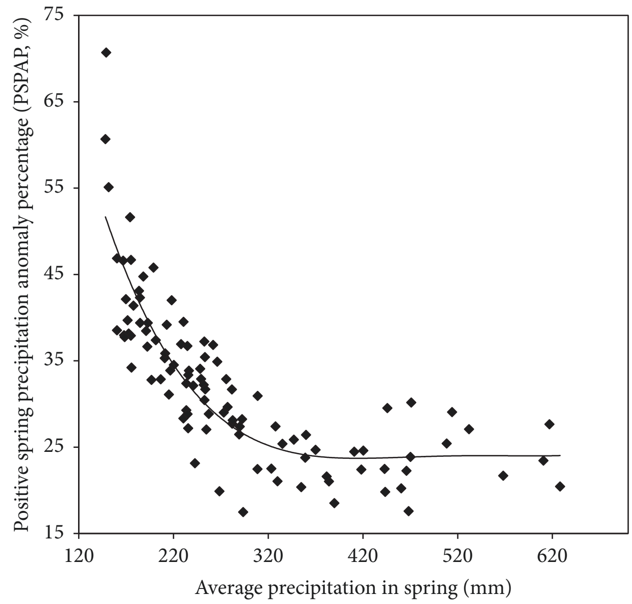

Figure 4: Relationship between the average PSPAP and the corresponding annual average precipitation for meteorological stations with winter wheat yield loss 1971–2010.

Table 4 shows the number of years with different level of S_p from 1971 to 2010. For the whole region, there were 10 years of local waterlogging, 4 years of regional waterlogging, and 5 years of large-scale regional waterlogging. There were 19 years of waterlogging occurrence with S_p at 10% and above, in which 1977, 1987, 1991, 1998, and 2002 were the most serious, and the occurrence rates of waterlogging at meteorological station level were 84.56%, 59.56%, 91.91%, 74.26%, and 69.85%, respectively (Figure 7). In addition, 1973, 1974, 1985, and 2010 were also severe waterlogging years. In 2010, there were 62.71% and 58.97% meteorological stations that had waterlogging in R2 and R3, respectively, while there was no waterlogging in R1, and this was the so-called south waterlogging. Similarly, only R1 and R2 had waterlogging but R3 was not influenced in 1974, and, correspondingly, we termed this phenomenon as the central and north waterlogging. The most severe winter wheat waterlogging occurred in 1991 when 91.9% meteorological stations had waterlogging, in which the moderate-to-severe waterlogging accounted for 76%.

4. Discussion

The precipitation is one of the major causes of waterlogging. In this study, we used the PAP and analyzed the

Table 4: Number of years of various waterlogging station proportions for winter wheat in the whole region from 1971 to 2010.

Region	Local waterlogging ($10\% \leqslant S_p < 25\%$)	Regional waterlogging ($25\% \leqslant S_p < 50\%$)	Large-scale regional waterlogging ($S_p \geqslant 50\%$)
Whole region	10	4	5

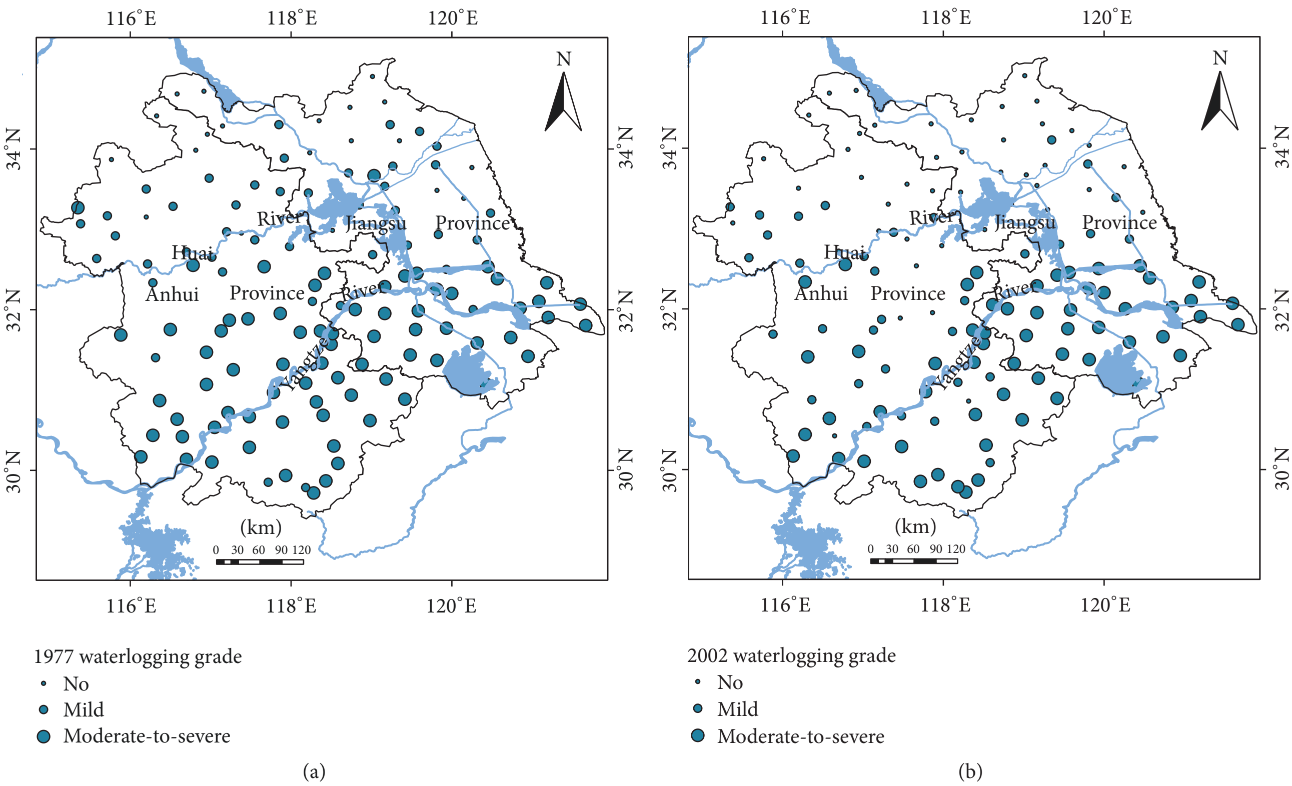

Figure 5: Spatial distribution of waterlogging severity in (a) 1977 and (b) 2002.

spatiotemporal characteristics of winter wheat waterlogging in spring during a relative long period. By analyzing the relationship between the relative meteorological yield and PAP during different growth stages of winter wheat, we found that the maximum negative correlation between the PAP and winter wheat yield appeared during the jointing to maturity stages (from March to May); previous studies also showed that winter wheat was most sensitive to waterlogging during this period [18, 33]. During the jointing stage of winter wheat, the waterlogging could significantly reduce biomass due to the decreased growth rate and increased tiller mortality [33, 34]. Prior to anthesis and milk stages of winter wheat, the waterlogging could cause the most significant reduction in grain weight [35].

We found that there were significant negative correlations between meteorological yield and SPAP for most meteorological stations (130 out of 136), while different places had varied loss rates even with the similar SPAP conditions but different average precipitations. This verified that PAPI might be misleading in areas with uneven precipitations [24]. To address this problem, we proposed the WPI index based on the yield loss rate and SPAP. We validated the effectiveness of WPI using the historical data of two years with severe waterlogging occurrences. The performance of WPI in waterlogging grading was satisfactory and generally consistent with the historical records in the study area. Compared with PAPI, the WPI could be effectively applied across regions with different precipitation patterns.

The maximum frequency (21–33%) of waterlogging mainly distributed in the south and regions along the Huai River in the study area. The south of the study area had higher occurrence of moderate-to-severe waterlogging (13–25%) while having less mild waterlogging. Actually, the regions along the Huai River in Anhui Province were significantly affected by the monsoon climate with relative larger precipitation variation than the southern regions (as shown in Figure 2). The north of Huai River was featured by relative large precipitation variation. As a consequence, this region could experience abrupt drought-flood transformation and, consequently, the so-called "flash waterlogging." A flash waterlogging means a severe, short-term waterlogging event characterized by excessive precipitation. The southern regions had relative large average precipitation, where the waterlogging could be incurred even with a slight increase in precipitation because the soil moisture is usually very high.

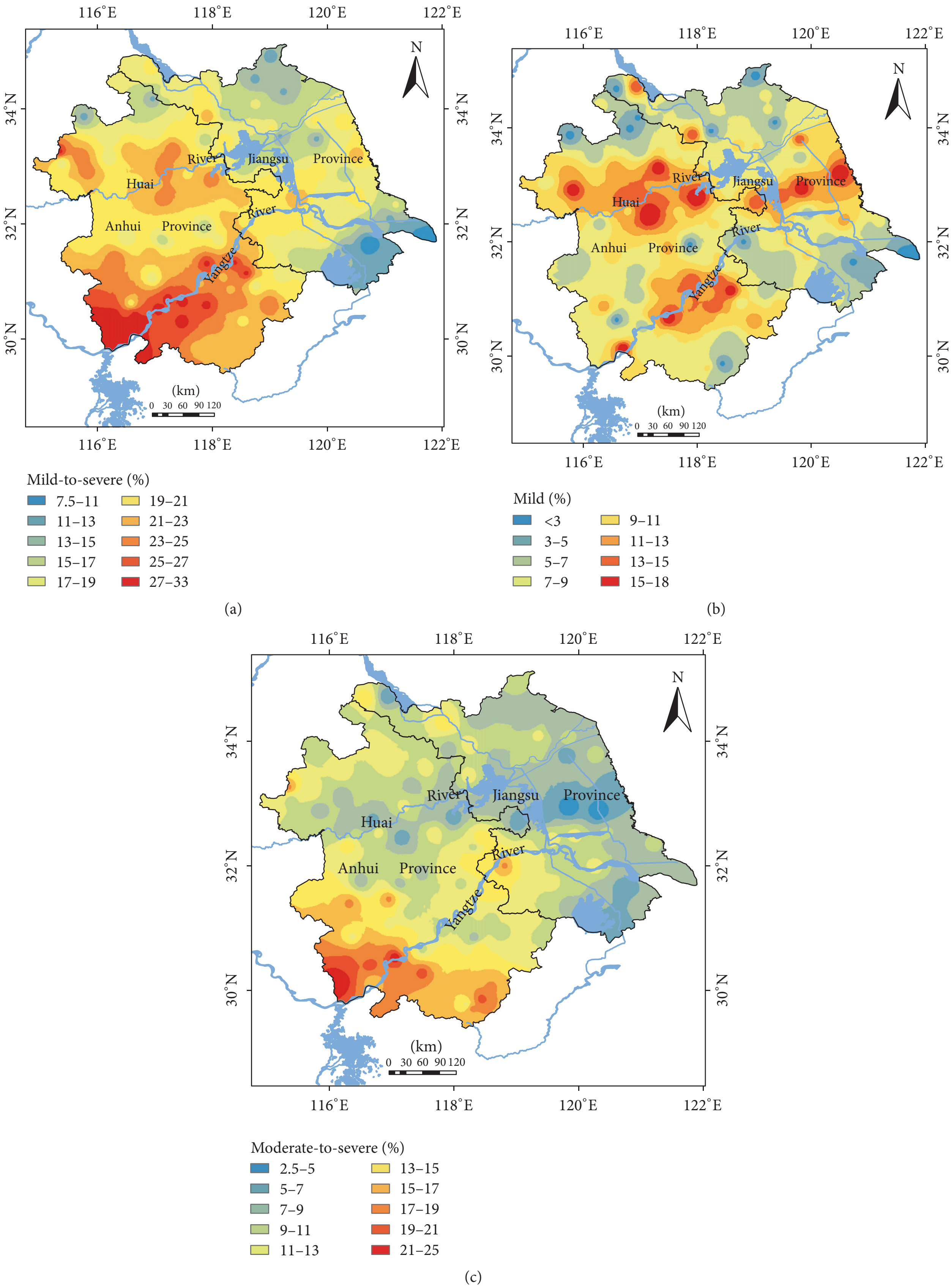

Figure 6: Spatial distribution of the winter wheat waterlogging frequency (in percent) estimated by the WPI in spring. (a) Mild-to-severe, (b) mild, and (c) moderate-to-severe waterlogging of winter wheat.

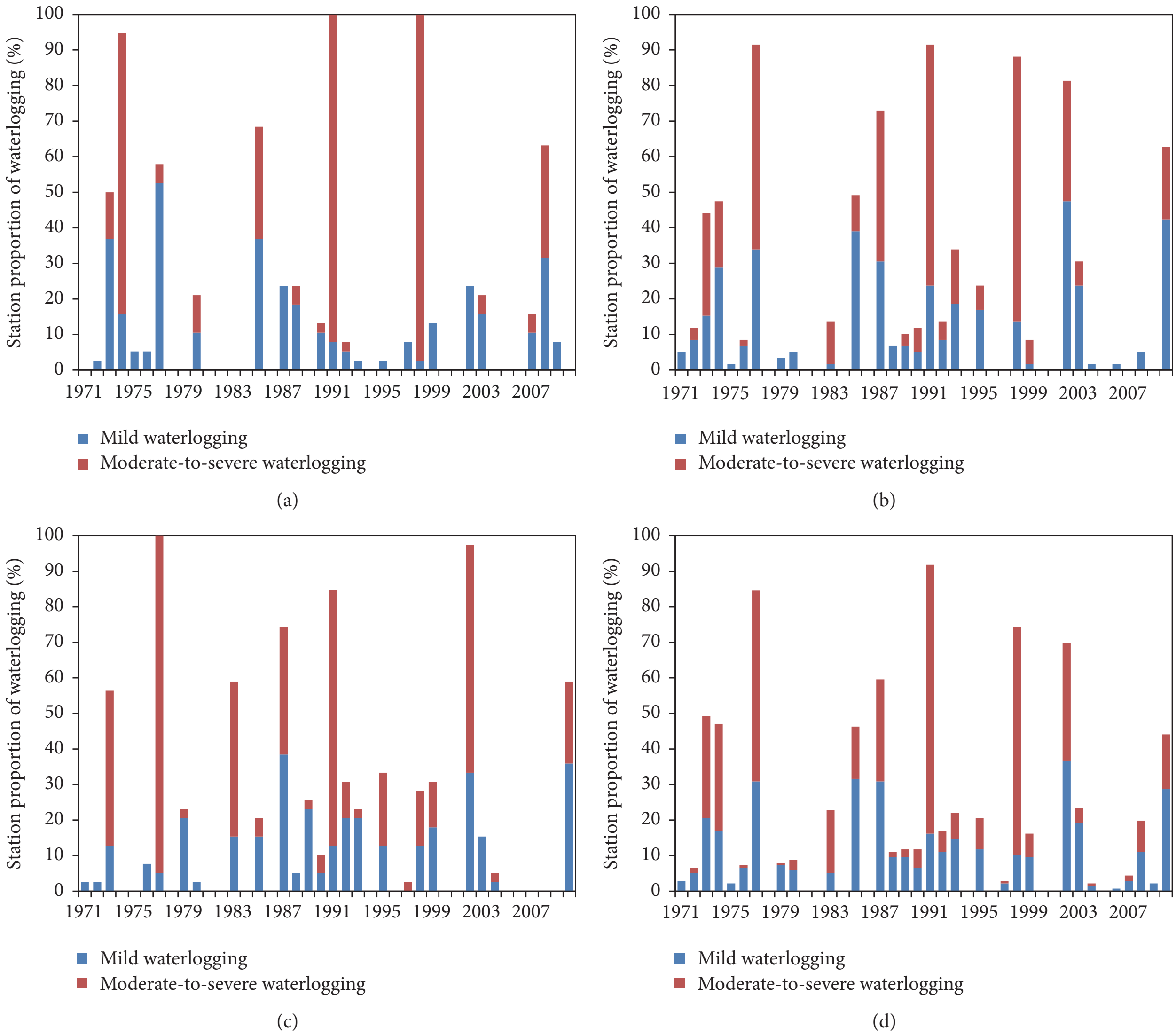

Figure 7: Proportion of winter wheat waterlogging in spring at meteorological station level for regions (a) R1, (b) R2, (c) R3, and (d) the whole region (R) during 1971 to 2010.

Previous studies showed that there were obvious spatial differences in extreme precipitation events in the study area [36, 37]. The north of Huai River did not show obvious extreme precipitation variation, but a prevailing trend of drying in spring and autumn and wetting in summer and winter had been observed [19, 20]. In the south of the study area along the Yangtze River, the precipitation intensity and heavy precipitation events both showed significant increasing trends, indicating that waterlogging disaster might become increasingly serious in this area [38–40].

The monsoon rainfall in the study area varied considerably in time, space, duration, and intensity [41]. The variations of monsoon rainfall often lead to disastrous waterlogging. The influences of EI Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) on precipitation over China had explicit annual and seasonal characteristics [42], but the linkage between waterlogging and ENSO/PSO is still not clear. Further studies about the driving mechanisms of precipitation pattern and the corresponding adaptive strategies are in urgent need to alleviate the influence of waterlogging in the study area.

Except meteorological factors, the degree of waterlogging is also partially determined by many nonmeteorological factors such as soil texture, topography, underground water table, and evapotranspiration rate [18]. The regions with clay, low-lying terrain, or high underground water level are more vulnerable to waterlogging [43]. For example, the northern part of Anhui Province dominated by the mortar black soil had higher frequency of waterlogging than the northern part of Jiangsu Province dominated by the sandy and loamy soil under the same precipitation conditions (Figure 6). In this study, we estimated the occurrence of winter wheat waterlogging by constructing a statistical index using precipitation and historical statistics data of winter wheat. It should be noted that the established WPI can be efficiently applied for the assessment of winter wheat waterlogging; however, it is not designed for the near real-time monitoring applications as the crop yield factor is included. In future studies, it would be intriguing to include more influential meteorological factors such as the amounts of rainy days, continuous rainy days, and the corresponding precipitation at different growth stages of certain crop, combined with crop physiological parameters, to establish more robust waterlogging monitoring indicators. To our understanding, a fully exploration about the mechanism and process of waterlogging for certain crops must take the properties of underlying land surface into consideration, including the physiological process of the target crop. From this point of view, a process-based land surface model might be necessary [44–48].

5. Conclusion

In this study, we investigated the spatiotemporal characteristics of winter wheat waterlogging in spring (March to May) in the middle and lower reaches of the Yangtze River during 1971–2010. The results showed that winter wheat waterlogging thresholds varied with the average precipitation in spring in different regions. The proposed WPI was effective in evaluating the severity of winter wheat waterlogging. The waterlogging frequency in the south of Huai River in Anhui Province was the highest in the study area. The south part of the study area was more prone to waterlogging than the north. The mid-1970s, late 1980s, and the 1990s were waterlogging-prone periods. The most serious waterlogging years during the study period were 1977, 1987, 1991, 1998, and 2002, in which 1991 was the most severe waterlogging year for winter wheat in spring.

This study provides a comprehensive assessment of the spatiotemporal characteristics of waterlogging for winter wheat. The technical framework and the waterlogging metric we proposed, that is, WPI, could be applied to other similar regions and is useful in waterlogging assessment.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

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Supplementary Materials

The supplementary materials include two figures (named "Figure S1" and "Figure S2") about the spatial distribution of winter wheat waterlogging for the waterlogging years of 1971 to 2010 over the study area. *(Supplementary Materials)*

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