ARTICLE

Analysis of the water balance and the nitrogen and phosphorus runoff pollution of a paddy field in situ in the Taihu Lake basin

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Abstract

Nitrogen (N) and phosphorus (P) runoff loads of paddy fields in situ under conventional water and fertilizer management measures caused severe water pollution in the Taihu Lake basin. The "water balance method" was implemented to calculate the surface runoff and the N and P runoff loads of the paddy field for 2 years. The total inflow difference in the paddy field between the 2 years was 22.5% with more irrigation and less precipitation in 2013 than in 2014. The soil water depletion of the paddy field was in the range of 47.0–83.3 mm, accounting for an average of 6.4% of the total inflow. The surface runoff was mainly caused by precipitation and artificial drainage, but irrigation return flow should not be neglected in paddy fields in situ. The rainfall runoff volume accounted for an average of 42.2% of the total precipitation. The artificial drainages occurred mainly during the tillering stage of drying, during maturity stage of drying and when the water level was too high in the paddy field. More than half of the irrigation cases would occur as irrigation return flow, which accounted for an average of 11.8% of the irrigation. The variation in N and P concentrations in the surface runoff of the paddy field was predominantly governed by the times of fertilization. Compared to the irrigation volume control, the runoff pollution loads were predominantly governed by the fertilization rate. The mean reduction potential of N and P fertilization was 38.9 kg ha^{-1} and 7.5 kg ha^{-1}, respectively. Reducing fertilizer rate is the effective way to improve the runoff pollution in paddy fields in the Taihu Lake basin.

Keywords Paddy field · Runoff pollution · Water balance · Nitrogen and phosphorus · Evapotranspiration

Introduction

Rice (*Oryza sativa* L.) as the most important staple food crop in Asia, especially in China, is relatively a heavy water consumer as relatively large water volumes are kept in fields (Ye et al. 2013). However, sustainable freshwater for rice production is increasingly becoming scarce and expensive due to the increasing water demand caused by serious regional and seasonal water shortages, population growth and competition from other sectors, such as rural urbanization, tourism industry and ecosystem services (Cao

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and Yin 2015; Rijsberman 2006; Sun et al. 2012). In China, the widely adopted water-saving irrigation technique is the alternate wetting and drying (AWD) irrigation, which is also referred to as the alternately submerged and non-submerged irrigation (Belder et al. 2004; Yao et al. 2012). In AWD irrigation, the irrigation water is applied to obtain flooded conditions after a certain number of days have passed after the disappearance of ponded water (Bouman et al. 2007a).

With the gradual process of point source pollution treatment in China, the water pollution caused by non-point source pollution (NSP), especially agricultural NSP, has become a prominent key problem (Ongley et al. 2010; Wang et al. 2013a). The severe blue-green algae bloom in the Taihu Lake in 2007 attracted world concern (Guo 2007). The Taihu Lake basin is one of the most densely populated and intensively cropped areas in China, of which approximately 75% of the arable land is exploited for rice cultivation (Peng et al. 2015). Pollution, e.g. nitrogen (N) and phosphorus (P), transferred from the flooded rice fields by direct flow through runoff warrants more attention (Bouman

et al. 2007b). High pollution of the surface field water can be found in the Taihu Lake basin, where fertilizer rates are high (Guo et al. 2004; Zhao et al. 2012a).

N and P are essential nutrients for crop growth, and the application of N and P is a key factor in the maintenance of high crop yields in intensive agricultural systems (Vitousek et al. 2010; Wang et al. 2014). N is the nutrient that most often limits crop production (Ladha et al. 2005). Paddy fields under high N fertilization and improper water management were potential sources for N pollution of the water in the Taihu Lake basin (Zhao et al. 2012a). N and P nutrient loss from arable lands where the nutrient level surpassed the crop demands was one of the major reasons for the deterioration of the water quality (Tian et al. 2007). The average utilization rate of fertilizer is only 30–35% (Jia et al. 2013; Zhang and Chen 2010). A high fertilizer input combined with a low nutrient use efficiency ultimately resulted in environmental problems such as serious agricultural NSP, soil degradation, eutrophication, groundwater pollution and emission of ammonia and greenhouse gases (Guo et al. 2010; Liu et al. 2015; Reidsma et al. 2012; Vitousek et al. 2009).

The water balance and runoff pollution of paddy fields could be analysed using runoff ponds (Chen et al. 2016; Huang et al. 2013) and synchronous observation of the runoff and pollution concentration (Choi et al. 2013), which has been widely used in practice. However, when using a runoff pond, a paddy field was required with a single outlet to build the runoff pond. The paddy fields also required a single and fixed outlet for synchronous observation of the runoff and pollution concentration. The two methods were mainly applied at experimental field sites (Zhou et al. 2016). In actual paddy fields in situ, the water balance and runoff pollution loads could be analysed by the "water balance method" based on synchronous observation of the precipitation and water depth (Huang et al. 2014; Zhou et al. 2016). Therefore, the surface runoff and runoff pollution characteristics of the paddy field in situ could be calculated and obtained without changing the original runoff characteristics and agricultural water management measures of the paddy field in situ. There have been a lot of studies for NSP of paddy fields. However, the runoff pollution of paddy fields in situ in the Taihu Lake basin is mainly affected by runoff characteristics or governed by excessive fertilization. What are the main types of paddy field runoff and what are the major influence factors? These all need to be further studied.

The objective of this study was to (i) calculate the surface runoff of a paddy field and analyse the difference between the water balance components for 2 years and (ii) calculate N and P runoff loads of a paddy field and analyse the main influence factors of runoff pollution. This study illustrated the water use and runoff pollution of paddy fields under conventional water and fertilizer management in the Taihu Lake basin. The information could illustrate how conventional agricultural water management affects paddy field runoff and reveal insights for reducing water pollution from paddy fields in situ in the Taihu Lake basin.

Materials and methods

Experimental site

The field experiment was conducted for 2 years (2013–2014) during the rice growing period at a paddy field in situ (31.4736°N, 119.4502°E), which was in Liyang, Changzhou, Jiangsu Province. The research area was located on the south bank of the lower reaches of the Yangtze River, in the western plain river network of the Taihu Lake basin and in the centre of the Yangtze River delta. It belongs to the subtropical humid monsoon climate. The annual mean temperature is 15.4 °C, the annual mean cumulative precipitation is 1071.5 mm, the annual mean sunshine duration is 2047.5 h, and the annual mean frost-free period is 227.6 days.
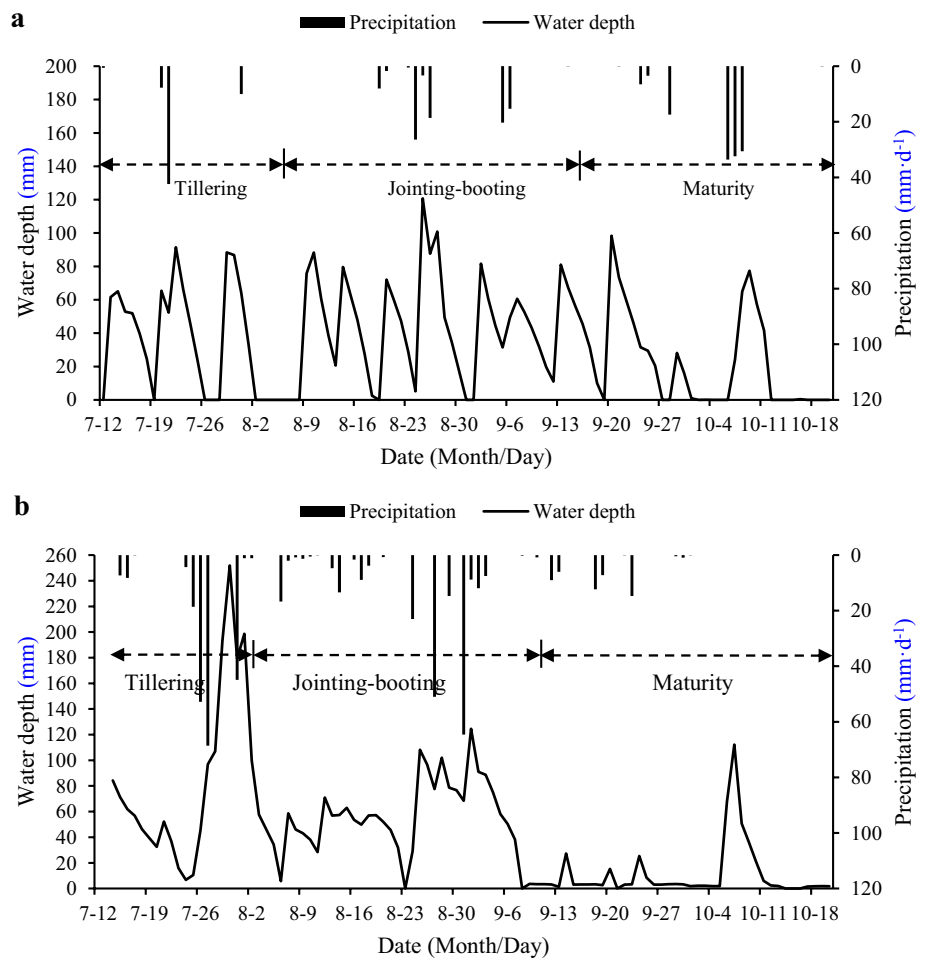
The typical paddy field chosen for observation was 900 m^2 and produced rice in rotation with wheat. Direct sowing and surface fertilizer application were applied in practice because of the convenience and low economic costs. The amount of fertilizer applied in the experimental paddy field was carried out in full accordance with local agricultural management measures. A compound fertilizer and urea were applied in the paddy field. The total N, P_2O_5 and K_2O application rates were 257.8, 46.7 and 53.3 kg ha^{-1} in 2013 and 220.0, 58.3 and 66.7 kg ha^{-1} in 2014, respectively. The AWD irrigation mode was adopted as the water-saving technology. The monitoring times were from July 12 to October 20 in 2013 and from July 14 to October 20 in 2014. The total monitoring period was 101 days in 2013 and 99 days in 2014, and the water balance of the paddy field was analysed. The growing period division, water depth and hyetograph of the paddy field are shown in Fig. 1. The monitoring period included the tillering stage, jointing–booting stage and maturity stage.

Thus, the results of this study were expected to be appropriately representative of the paddy fields under conventional water and fertilizer management in the Taihu Lake basin.

Data collection

The data used in this paper included precipitation and water depth in the paddy field and fundamental meteorological data of Liyang. The precipitation and water depth were collected during the rice growing period for 2 years using a pluviograph and an automatic mareograph. The observation frequency of the water depth was 30 min, while that of the precipitation was 10 min. A pluviograph

Fig. 1 Growing period division, water depth and hyetograph of the paddy field in 2013 (**a**) and 2014 (**b**)

Calculation and analysis

Water balance analysis

The variation in the water depth in the paddy field depends mainly on precipitation, irrigation, evapotranspiration, infiltration and runoff. When there is always water in a paddy field, the water variation could be calculated using the water balance model (Khepar et al. 2000; Tsubo et al. 2005). Water balance equation is shown as follows:

$$P + R_{in} - ET - F - R_{out} = \Delta H \tag{1}$$

where P is the daily precipitation (mm d^{-1}), R_{in} is the irrigation water inflow (mm d^{-1}), ET is the evapotranspiration (mm d^{-1}), F is the infiltration loss (mm d^{-1}), R_{out} is the surface water outflow (mm d^{-1}) and ΔH is the depth variation (mm d^{-1}).

Based on water balance Eq. (1), the irrigation and runoff of the paddy field could be calculated by daily precipitation, water depth difference between the first and second days, ET

was installed on a fixed tripodal platform in the target plot, and a rain barrel was kept vertically and 70 cm away from the ground. An automatic mareograph was installed near the ridge in the paddy plot, and the mareograph probe was installed approximately 2 cm above the field bottom to avoid blocking by mud. The probe installation height remained unchanged during the growing period.

The fundamental meteorological data were obtained from the Liyang Meteorological Station (31.26° N, 119.29° E), which was on a daily scale, and included the cumulative precipitation (mm); average relative humidity (%); mean wind speed (m s^{-1}); sunshine duration (h); maximum, minimum and mean air temperature (°C); and daily net radiation (MJ m^{-2}).

During the rice monitoring period, the water samples were collected at a fixed point approximately one metre from pluviograph twice a week. The water samples were sent to the laboratory for analysis and determination of the monitoring indexes of total N, NH$_4^+$–N (ammonia nitrogen), NO$_3^-$–N (nitrate nitrogen), total P and PO$_4^{3-}$–P (orthophosphate).

and F, as shown in Eq. (2) (Huang et al. 2014; Zhou et al. 2016):

$$
\begin{cases}
\Delta R_i = P_i - \mathrm{ET}_i - F_i - \left(H_{i+1} - H_i\right) \\
\Delta R_i > 0, R_{\mathrm{out},i} = \Delta R_i \\
\Delta R_i < 0, R_{\mathrm{in},i} = -\Delta R_i
\end{cases}
\tag{2}
$$

where P_i is the precipitation (mm d^{-1}) of day i, ET_i is the evapotranspiration (mm d^{-1}) of day i, F_i is the infiltration (mm d^{-1}) of day i, H_i is the water depth (mm) of day i, H_{i+1} is the water depth (mm) of day $i+1$, ΔR_i is the difference value (mm d^{-1}) between the water inflow and outflow of day i, $R_{\mathrm{in},i}$ is the paddy irrigation of water (mm d^{-1}) of day i and $R_{\mathrm{out},i}$ is the paddy outflow of water (mm d^{-1}) of day i.

$\sum R_{\mathrm{in},i}$ is the total irrigation volume (mm) during the rice growing period, and $\sum R_{\mathrm{out},i}$ is the total surface runoff volume (mm).

($E + F$) estimation in a steadily declining water level period

The factors influencing the water depth included natural factors and artificial factors. The natural factors mainly included evapotranspiration and infiltration ($E + F$) and precipitation. The artificial factors mainly included irrigation and artificial drainage. When there were no rainfall, irrigation, and artificial drainage, the water depth variation process line was only affected by ($E + F$) processes (Huang et al. 2014). Therefore, Eq. (1) can be simplified as follows:

$$
-(E + F) = \Delta H
\tag{3}
$$

The ($E + F$) term can be estimated by determining the steady decline in the water level that was selected to calibrate ($E + F$) by determining the steady decrease rate based on synchronous observation of the precipitation and water depth.

Evapotranspiration calculation

The crop coefficient method with the recommended FAO-56 Penman–Monteith equation (Allen et al. 1998) was applied to calculate the daily evapotranspiration of the paddy field with synchronous meteorological data. In this paper, the single crop coefficient method was applied. The rice evapotranspiration (ET_c), which accounted for soil evaporation and rice transpiration, was calculated as follows:

$$
\mathrm{ET}_c = K_c \times \mathrm{ET}_0
\tag{4}
$$

where ET_c is the daily evapotranspiration (mm d^{-1}) of the paddy field, ET_0 is the reference crop evapotranspiration (mm d^{-1}) and K_c is the rice coefficient.

The values of K_c at different rice growth stages were taken from FAO irrigation and drainage paper (Allen et al.

1998). Water was kept in the paddy field for most of the time, so it was assumed that there was no water stress for rice growth during the monitored growing period except in the late maturity stage.

Infiltration estimation and ($E + F$) estimation within the rice growing period

The infiltration of paddy fields included percolation and seepage. The percolation through the plough sole of a paddy field could be assumed to be like that of soil with a similar texture. The percolation of the paddy field could be obtained from related studies in the Taihu Lake basin. Then, in the steadily declining water level period, the seepage of the paddy field could be calculated as Eq. (5):

$$
S = (E + F) - \mathrm{ET}_c - C
\tag{5}
$$

where S is the daily seepage (mm d^{-1}), ($E + F$) is the estimated evapotranspiration and infiltration (mm d^{-1}) by determining the steady decrease rate of the water level and C is the average percolation (mm d^{-1}) of paddy fields in the Taihu Lake basin.

With the average seepage of different growth stages of the paddy field obtained, the average infiltration of different growth stages was added by the average seepage and average percolation values. After adding the average infiltration of different growth stages and the daily ET_c, the daily ($E + F$) in the growing period was acquired. Therefore, the water balance of the paddy field could be calculated using Eq. (2).

Irrigation identification based on the water depth

The paddy field would be irrigated many times during the rice growing period to satisfy the rice water demand for healthy growth. When artificial irrigation began, the water level rose rapidly and there was an irrigation flexion in the water depth variation process line. When the irrigation ended, the paddy field achieved the maximum irrigation water depth. Then, the water level would drop slowly. Figure 2 shows a typical water depth hydrograph with irrigation. The difference in the water depth before and after irrigation was the artificial irrigation volume for this time, as shown in Eq. (6):

$$
I_j = H_p - H_q
\tag{6}
$$

where H_p is the maximum water depth (mm) at the end of artificial irrigation, H_q is the water depth (mm) at the beginning of artificial irrigation and I_j is the irrigation volume (mm) for this time.

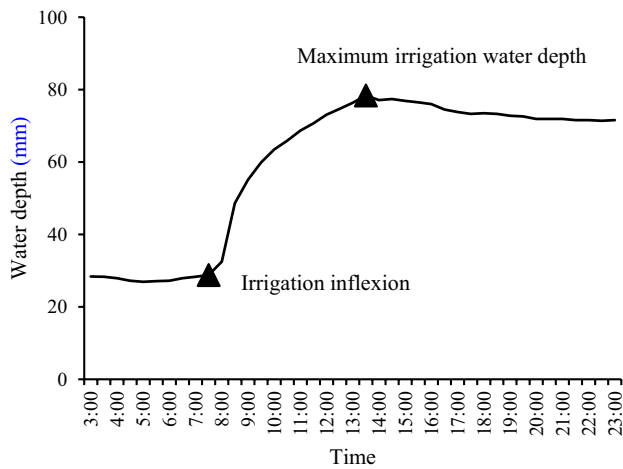$\sum I_j$ is the total irrigation volume during the rice growing period.

Fig. 2 Water depth hydrograph with artificial irrigation

Runoff pollution calculation

It was difficult to determine the pollution concentration of every runoff in the paddy field in situ, so the paddy field water was collected and analysed regularly. The pollution concentration variation process during the growing period was obtained by the interpolation method. The runoff pollution was calculated by multiplying the runoff volume with the pollution concentration [Eq. (7)] as follows:

$$L_i = R_{out,i} \times C_i \tag{7}$$

where L_i is the N or P runoff pollution (mg m^{-2} d^{-1}), $R_{out,i}$ is the runoff volume (mm d^{-1}) and C_i is the N or P runoff concentration (mg l^{-1}).

$\sum L_i$ is the total N or P runoff load (kg ha^{-1}) during the whole rice monitoring period.

Statistical analysis

Statistical analysis was performed using SPSS version 20.0 (SPSS, Chicago, Illinois, USA). The difference between the means was analysed using analysis of variance (ANOVA) with the least significant difference test at the 0.05 probability level. Bivariate correlation with the Pearson correlation coefficient was used to analyse the correlation between the ET$_c$ and meteorological data.

Results and discussion

Water balance analysis of the paddy field

The variation in the water depth depended on the inflow of water and the consumption of water in paddy fields. The inflow of water included precipitation and irrigation, and the consumption of water included evapotranspiration, infiltration and surface runoff. The rainfall runoff in paddy fields was closely correlated with the rainfall and the lowest ridge height (Zhao et al. 2009). The surface runoff during the rice growing season of rice–wheat rotation was predominantly due to variable natural precipitation and frequently occurring irregular artificial draining (Zhao et al. 2012a). Heavy rainfall for consecutive days and extreme rainstorm events were the main factors determining the occurrence and the amount of surface runoff, while a high water level was another factor contributing to the occurrence of surface runoff in paddy fields (Ye et al. 2013). The water level would exceed the lowest ridge height and flow out of the paddy field, if the paddy field was irrigated with too much water. The portion of the irrigation water flowing to drainage ditches or channels was the irrigation return flow or excess irrigation water, which was defined as the quick return flow in Kim's study (Kim et al. 2009). This would occur in actual paddy fields in situ with extensive agricultural water management.

The surface runoff of the paddy field included rainfall runoff, drainage runoff and irrigation return flow. The water balance analysis of the paddy field with the AWD irrigation method usually assumed that groundwater capillary rise was usually negligible in the water balance of the paddy field (Inthavong et al. 2011), because there was a continuous downward flow of water (percolation) from the puddled layer to below the plough sole that basically prevented the capillary rise to the root zone (Bouman et al. 2007b).

Evapotranspiration of the paddy field

The values of ET$_c$ of the paddy field in 2013 and 2014 were calculated with the Penman–Monteith equation. As shown in Fig. 3, the average ET$_c$ of the paddy field decreased
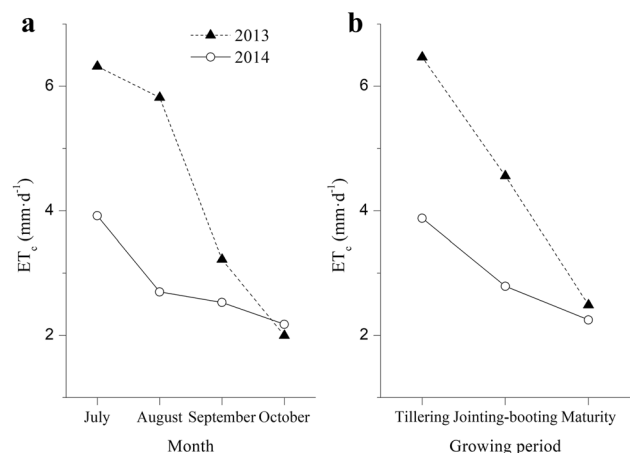

Fig. 3 The average ET$_c$ variation between 2013 and 2014 in the different months (**a**) and different growing periods (**b**)

gradually from the tillering stage to the maturity stage and from July to October in the growth months of both 2013 and 2014. The total ET_c during the monitoring period of the paddy field in 2013 was 443.5 mm, which was greater than the total ET_c of 273.7 mm in 2014. Using ANOVA, the means of the ET_c in 2013 and 2014 were significantly different at the 0.05 probability level.

The Pearson correlation between the ET_c and meteorological data was analysed. As shown in Table 1, the values of ET_c were significantly negatively correlated with the cumulative precipitation and average relative humidity and significantly positively correlated with the mean air temperature and daily net radiation at the 0.01 level in both 2013 and 2014. The meteorological data comparison is shown in Fig. 4. Except for October, the mean air temperature and average daily net radiation in 2013 were higher than those in 2014, and cumulative precipitation and average relative humidity in 2013 were less than those in 2014. This explains why the ET_c in 2013 was greater than that in most of 2014. The variations of cumulative precipitation, reflecting the weather conditions, were consistent with the variations of other meteorological factors. The cumulative precipitation is a significant meteorological factor influencing the ET_c of the paddy field.

($E + F$) of the paddy field

(1) ($E + F$) estimation during the steadily declining water level period.

Calculated by determining the steady decrease rate of the water level with the "in situ method based on synchronous observation of the precipitation and water depth", the ($E + F$) during the steadily declining water level period was acquired. There were 45 ($E + F$) determinations in total of 2013 and 30 ($E + F$) determinations in total of 2014. With ANOVA, there was no significant difference between the ET_c in 2013 and the ET_c in 2014. The maximum, minimum and mean values of the ($E + F$) were 15.72, 5.36 and 10.86 mm d^{-1} in 2013 and 12.89, 5.49 and 9.88 mm d^{-1} in 2014, respectively.

(2) Infiltration estimation of the paddy field.

The magnitude and consistency of the infiltration rate of the paddy field were affected by the physical and hydraulic soil properties of the plough sole and the underlying subsoil, such as the structure, texture and conductivity of different layers, and by the hydrologic environment (Bouman et al. 1994; Lin et al. 2014). In the study, which was conducted in Yixing, Taihu Lake basin, in a paddy field with the same soil classification and texture, the average rate of the vertical percolation was 2 mm d^{-1} calculated from 15 replicate measurements (Zhao et al. 2012a). The average percolation rate of another experimental paddy field in the Taihu Lake basin was 2.57 mm d^{-1} (Wang et al. 2014). According to the actual observed statistic data from Jiangsu province, the vertical infiltration rate of a single crop rice region with clay soil, loam soil and sandy loam soil was 1.2–4, 2.1–5.3 and 5.5–9.8 mmvd^{-1}, respectively (Wu 2015). Therefore, in this study, we assumed the percolation rate to be 2.6 mm d^{-1} (the mean of 1.2–4 mm d^{-1}) based on the loamy clay soil texture of the paddy field.

The average seepage rate of the paddy field was 3.6 mm d^{-1} in 2013 and 4.1 mmvd^{-1} in 2014 based on Eq. (5). With ANOVA, there was no significant difference between the seepage rate in 2013 and that in 2014. The study carried out in Taiwan indicated that the vertical infiltration and lateral seepage rates of a flat paddy field through the bottom of the ridge were 4.0 and 3.3 mm d^{-1}, respectively, with the plough sole underneath (Huang et al. 2003).

(3) ($E + F$) estimation in the rice monitoring period.

With the assumed percolation and calculated seepage rate, the daily infiltration rate was obtained. Then, the ($E + F$) of the paddy field during the water depth variation mutation period could be acquired by adding the daily infiltration rate to the ET_c. When there was no ponded water in the paddy field, only the ET_c occurred through absorption of water by the soil body. The total ($E + F$) of the paddy field was calculated as 875.6 mm in 2013 and 674.0 mm in 2014.

Table 1 The Pearson correlation of the ET_c with the cumulative precipitation, mean air temperature, average relative humidity and daily net radiation

		Cumulative precipitation	Mean air temperature	Average relative humidity	Daily net radiation
2013 ET_c	Pearson correlation	− 0.414[a]	0.824[a]	− 0.762[a]	0.959[a]
	Sig. (two-tailed)	0.000	0.000	0.000	0.000
	Number	101	101	101	101
2014 ET_c	Pearson correlation	− 0.270[a]	0.608[a]	− 0.400[a]	0.963[a]
	Sig. (two-tailed)	0.007	0.000	0.000	0.000
	Number	99	99	99	99

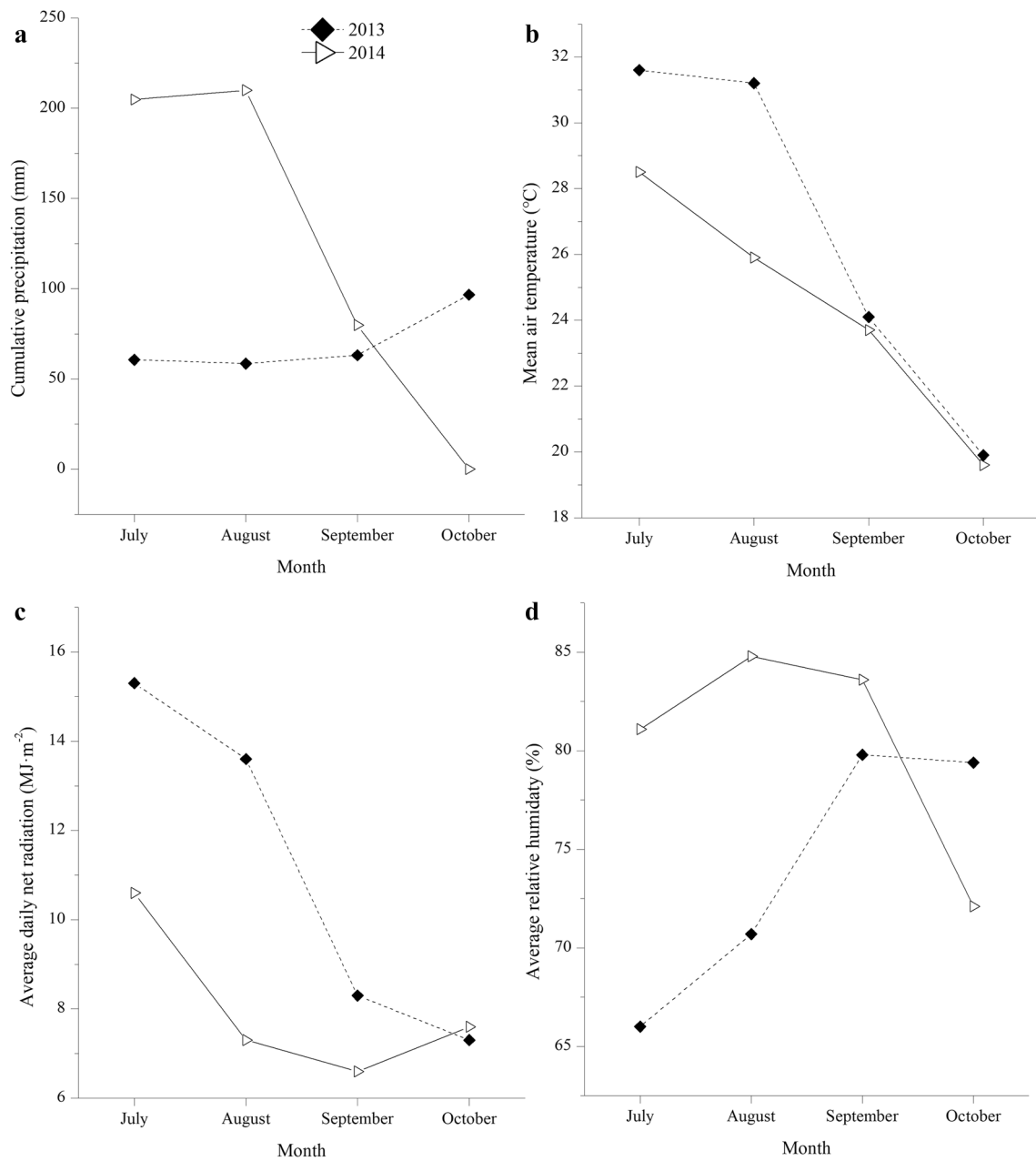[a]The correlation is significant at 0.01 level

Fig. 4 Main meteorological factors comparison of the cumulative precipitation (**a**), mean air temperature (**b**), daily net radiation (**c**) and average relative humidity (**d**) in 2013 and 2014

Irrigation of the paddy field

Table 2 shows the total irrigation calculated by Eq. (2) and the irrigation identification method of Eq. (6). The irrigation times analysed by the two methods were the same in the 2 years, with 10 irrigation times in 2013 and 7 irrigation times in 2014. The irrigation volumes analysed by the two methods had an absolute difference of 1.1–6.8%, which illustrates the accuracy of the two methods for irrigation

Table 2 Irrigation times and volume (mm) analysed by the two methods of the paddy field

Year	Irrigation times	Irrigation volume (mm)		
		Water balance method	Irrigation identification method	Difference (%)
2013	10	879.9	823.7	6.8
2014	7	451.5	456.5	− 1.1

analysis and the feasibility of the "water balance method" for water balance analysis in paddy fields. The "irrigation identification method based on the water depth" can be used for comparative analysis of the irrigation volume.

There was more irrigation in 2013 than in 2014 because the total precipitation level during the monitoring period in 2014 of 494.7 mm was much greater than that in 2013, namely 279.0 mm. To ensure the healthy growth of rice with enough water, the paddy field was irrigated with more water when the precipitation was lacking.

Surface runoff of the paddy field

(1) Rainfall runoff.

Figure 5 shows the rainfall runoff and the precipitation causing runoff during the monitoring period in 2013 and 2014. There were 6 rainfall runoff times with a total volume of 124.8 mm in 2013 and 5 rainfall runoff times with a total volume of 201.8 mm in 2014. The rainfall runoff volume in 2013 accounted for 44.7% of the total precipitation during the monitoring period and that in 2014 accounted for 40.8% of the total precipitation. There were 14 precipitation events during the monitoring period in 2013 and 20 precipitation events in 2014. According to the statistics, 2 of the 3 heavy rain events, 2 of the 4 moderate rain events and 3 of the 7 light rains in 2013, and all 4 of the rainstorms, 1 heavy rain event, 2 of the 10 moderate rain events and 1 of the 5 light rains in 2014 caused rainfall runoff. All of the rainstorms,

most of the heavy rains, some of the moderate and light rains caused rainfall runoff. The greater precipitation volume caused by heavy precipitation in 2014 resulted in more rainfall runoff than in 2013.

Moderate rain and light rain caused rainfall runoff when a high water level was maintained in the paddy field or when a low ridge height of the paddy field was maintained during the maturity stage. Thus, the rainfall runoff was related to the precipitation level, water depth and ridge height of the paddy field.

(2) Drainage runoff.

Figure 6 shows the drainage runoff during the monitoring period in 2013 and 2014. There were 4 drainage runoff events with a total volume of 125.9 mm in 2013 and 3 drainage runoff events with a total volume of 76.6 mm in 2014. There were 2 drainage runoffs in 2013 and 1 drainage runoff in 2014 during the tillering stage of drying, which was practiced to promote moderate tillering, and the reproductive health of the rice crop by impeding the excessive tillering of rice (Tan et al. 2013). The last drainage event in both 2013 and 2014 was during the maturity stage of drying. There was one drainage event during jointing–booting stage in both 2013 and 2014, due to the high water depth in the paddy field caused by irrigation or continuous precipitation. Then, artificial drainage mainly occurred during the tillering stage of drying, during maturity stage of drying and when the water level was too high in the paddy field, which were routine agricultural water management measures.
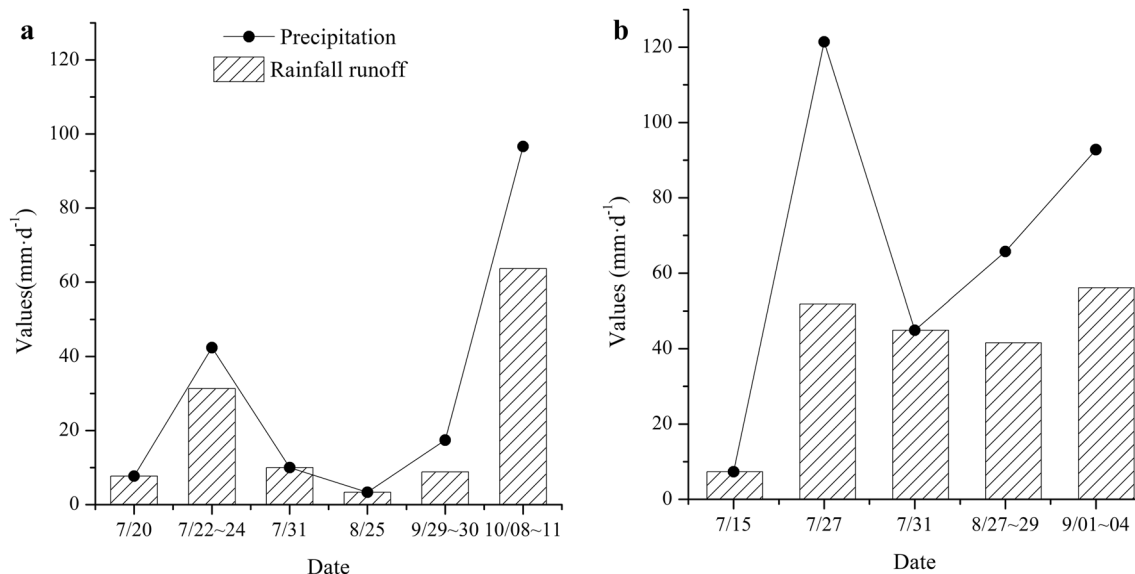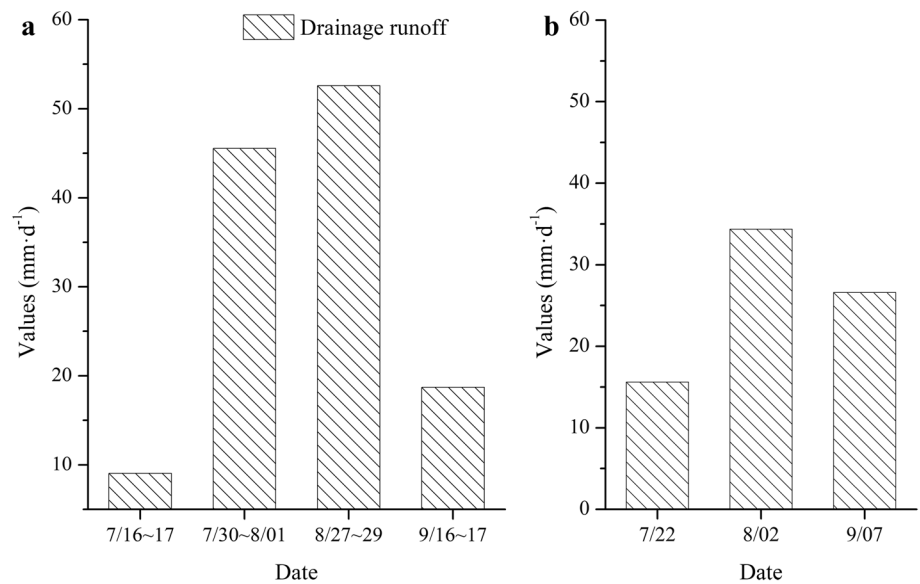

Fig. 5 Rainfall runoff of the paddy field in 2013 (**a**) and 2014 (**b**)

Fig. 6 Drainage runoff in the paddy field in 2013 (**a**) and 2014 (**b**)

(3) Irrigation return flow.

Figure 7 shows the irrigation return flow during the monitoring period in 2013 and 2014. There were 5 irrigation return flows with a total volume of 79.6 mm in 2013 and 4 irrigation return flows with a total volume of 77.1 mm in 2014. The irrigation return flow in 2013 accounted for 9.0% of the total irrigation during the monitoring period and that in 2014 accounted for 17.1% of the total irrigation. The irrigation return flow accounted for an average of 11.8% of the irrigation. More than half of the irrigation cases would occur as irrigation return flow, which was related to the extensive agricultural irrigation measures in the paddy field in situ.

(4) Surface runoff analysis.

The surface runoff in the paddy field was 330.3 mm in 2013 and 355.4 mm in 2014; the runoff values were similar between the 2 years with a difference of 7.1%. Table 3 differentiates the contribution of the different runoff sources to the surface runoff in 2013 and 2014. The average data from the 2 years show that 47.3% of the surface runoff was caused by precipitation, 29.8% by drainage and 22.9% by irrigation. The precipitation and artificial drainage led to most of the surface runoff, as most research was implemented in site paddy fields without irrigation return flow (Tan et al. 2015; Zhao et al. 2012a). However, in actual paddy fields in situ
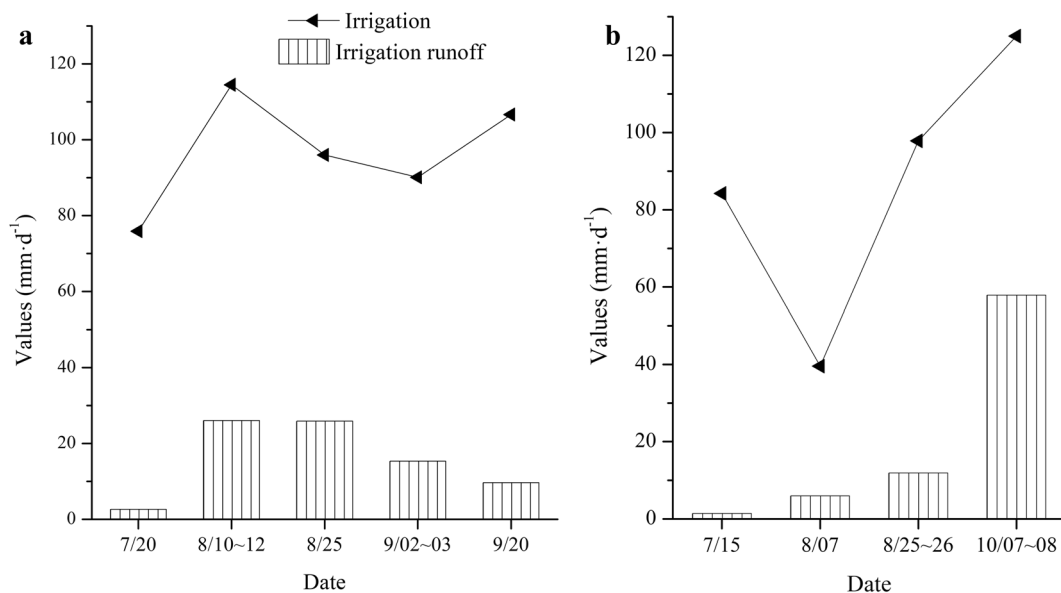

Fig. 7 Irrigation return flow of the paddy field in 2013 (**a**) and 2014 (**b**)

Table 3 Contribution of the different runoff sources to the surface runoff in 2013 and 2014 (%)

Year	Rainfall runoff	Drainage runoff	Irrigation return flow
2013	37.8	38.1	24.1
2014	56.8	21.5	21.7
Average	47.3	29.8	22.9

Table 4 Proportion of the surface runoff in different growing periods in 2013 and 2014 (%)

Year	Tillering	Jointing–booting	Maturity
2013	32.2	39.1	28.8
2014	34.1	49.7	16.3
Average	33.1	44.4	22.5

with extensive agricultural water management, the irrigation return flow was a common phenomenon. As shown in this study, the irrigation return flow should not be neglected in paddy fields in situ.

Table 4 shows the proportion of the surface runoff in different growing periods in 2013 and 2014. The greatest surface runoff in the paddy field occurred during the jointing–booting stage, with an average proportion of 44.4%, and the least occurred during the maturity stage.

Water balance analysis

Table 5 shows the water balance analysis results of the paddy field in 2013 and 2014. The total inflow consisting of precipitation and irrigation during the monitoring period was 1158.9 mm in 2013 and 946.2 mm in 2014, with a difference of 22.5% and more 212.8 ml in 2013 than in 2014. There was more irrigation due to less precipitation in 2013 than that in 2014 of the paddy field. The water management measures of the paddy field were adjusted to the weather conditions, and there was a tendency of excessive irrigation with less precipitation to the paddy field. As analysed, the surface runoff between the 2 years was similar, but the $(E+F)$ between the 2 years was different mainly because of the significant differences in the value of ET_c.

As calculated, the soil water depletion of the paddy field was 47.0 mm in 2013 and 83.3 mm in 2014, which accounted for 4.1% of the total inflow in 2013 and 8.8% in 2014 with an average ratio of 6.4%. Because the paddy field was ponded and the paddy soil at the beginning of the rice growing period was saturated and dried at the end, the water depletion was regarded as the soil water consumption for the rice growth (Tan et al. 2014). In the study, the soil water depletion in the paddy field with AWD irrigation was approximately 100–200 mm (Tan et al. 2015).

Runoff pollution load of the paddy field

N and P runoff concentrations

Figure 8 shows the variation in the N and P concentrations in the surface runoff of the paddy field in 2013 and 2014. The variation was predominantly governed by the times of fertilization. The N concentration was high within 1 week after N fertilizer application, while the P concentration was relatively high within 2 weeks after P fertilizer application. Then, the N and P concentrations were low and stable in the paddy field water over time. This was consistent with the N concentration variation in paddy fields in related studies (Tian et al. 2007; Zhao et al. 2012a). The variation difference between N and P was related to the different release rates of N and P fertilizer. After fertilizer application, the dissolved N and particulate P were the main forms in the paddy field. The particulate P, which was the main form of P loss in the runoff, was adsorbed on soil particles with a low release rate (Chen et al. 2016). More than 90% of total P in the runoff was lost through suspended particles (Wang et al. 2013b).

The most N concentration in 2013 was higher than that in 2014, which was mainly related to the more N fertilizer applied to the paddy field in 2013. The most PO_4^{3-}–P concentration in 2013 was lower than that in 2014, mainly related to less P fertilizer applied to the paddy field in 2013. The NH_4^+–N and NO_3^-–N concentrations were consistent with the total N concentration, while the PO_4^{3-}–P concentration was consistent with the total P concentration. There were two P concentration declines after fertilization application on July 10, 2013. This could be due to the two irrigations on July 12 and July 19, which diluted the P concentration.
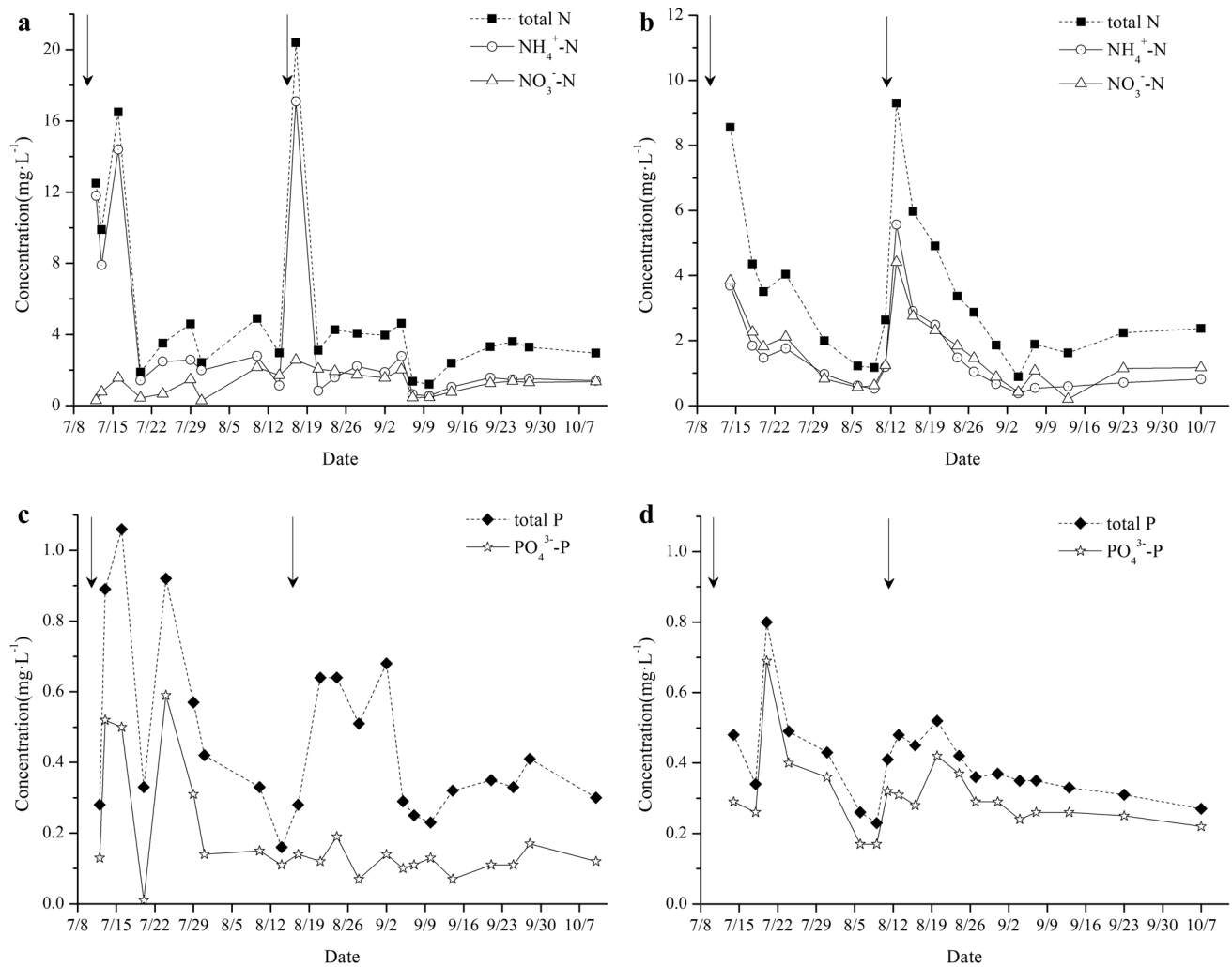
Table 5 Water balance analysis of the paddy field in 2013 and 2014 (mm)

Year	Precipitation	Irrigation	Total inflow	Surface runoff	$(E+F)$	Water depletion
2013	279.0	879.9	1158.9	330.3	875.6	− 47.0
2014	494.7	451.5	946.2	355.4	674.0	− 83.3

Fig. 8 Variation in the N and P concentrations in the surface runoff in the paddy field in 2013 (**a**, **c**) and 2014 (**b**, **d**). The arrow denotes the timing of fertilization

N and P runoff loads

According to previous studies, precipitation, irrigation, fertilization and ridge height had a significant effect on the runoff pollution loads of paddy fields (Chen et al. 2016; Wang et al. 2013b; Zhao et al. 2012b). With the N and P concentration and surface runoff volume, the N and P runoff pollution of the paddy field could be calculated by Eq. (7). Figure 9 shows the variation in the surface runoff and the N and P runoff pollution of the paddy field in 2013 and 2014. There were 12 surface runoff times in 2013 and 10 surface runoff times in 2014. As shown in Fig. 9, the variations in the N and P runoff pollution were relatively consistent with the surface runoff volume.

As shown in Fig. 10, the runoff pollution loads of total N, NH_4^+–N, NO_3^-–N, total P and PO_4^{3-}–P of the paddy field were 12.18, 7.13, 4.15, 1.55 and 0.53 kg ha^{-1} during the monitoring period in 2013 and 8.59, 3.50, 4.17, 1.36 and

1.09 kg ha^{-1} in 2014, respectively. The N runoff loads in 2013 were greater than those in 2014 with more N fertilizer applied to the paddy field in 2013, even though the surface runoff volume was less in 2013 than in 2014. This indicated that N runoff losses were more dependent on N concentrations in the runoff water than the runoff volume. This was similar to a previous study (Jin et al. 2006; Tian et al. 2007), in which no relationship between the total N load and runoff volume was found after N fertilizer was applied at a high rate. The total P runoff loads were near between the 2 years, but the PO_4^{3-}–P runoff loads in 2013 were less than those in 2014 because of less P fertilizer application in 2013.

The ratio of NH_4^+–N to total N ranged from 40.7 to 58.5%, with an average of 49.6%. The ratio of NO_3^-–N to total N ranged from 34.0 to 48.5%, with an average of 41.3%. Nitrate and ammonia were both the main forms of total N runoff pollution in the surface runoff in the paddy field. The ratio of PO_4^{3-}–P to total P ranged from 34.2 to 79.7%, with

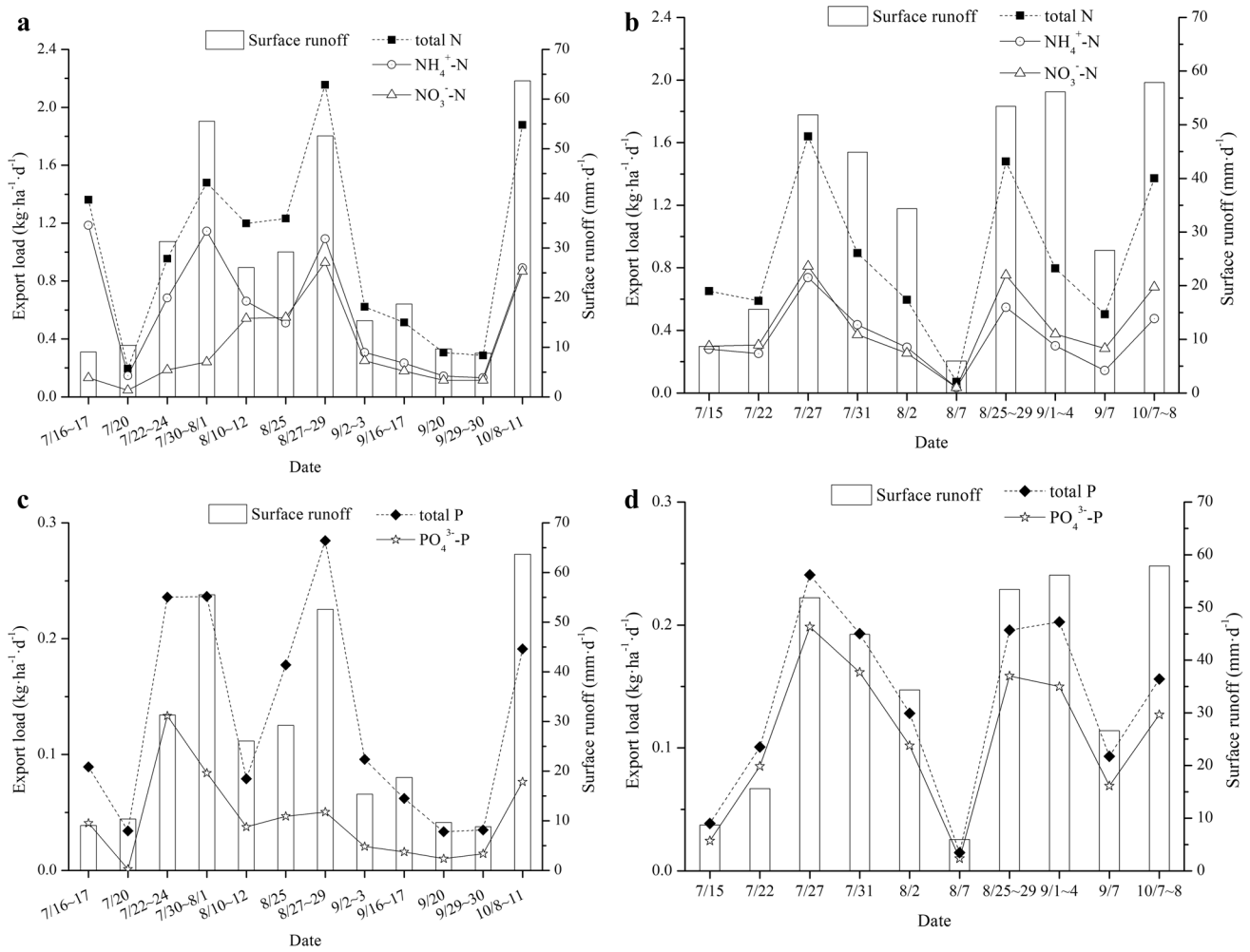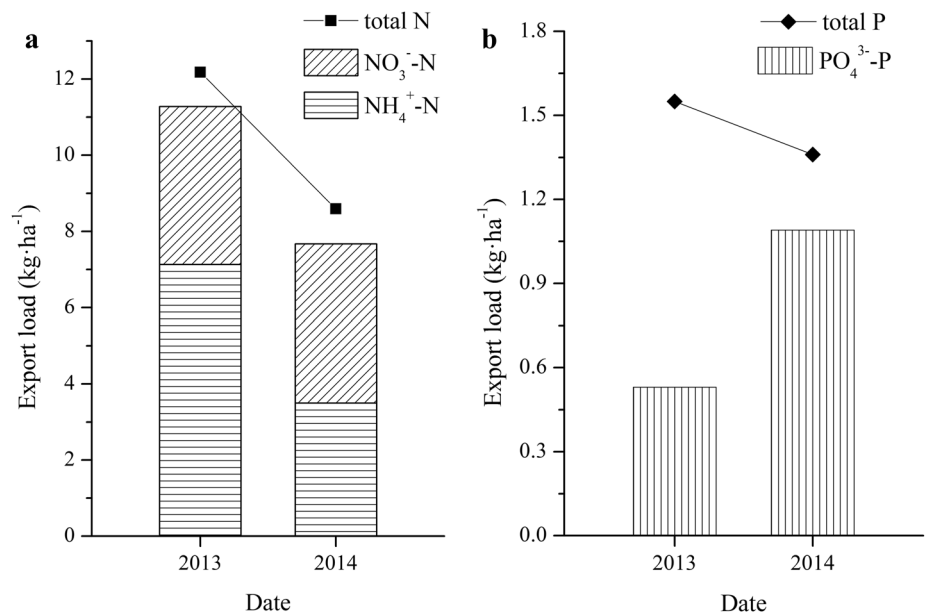**Fig. 9** Variation in the surface runoff and the N and P runoff loads of the paddy field in 2013 (**a**, **c**) and 2014 (**b**, **d**)

Fig. 10 Export loads of total N, NH_4^+–N and NO_3^-–N of the paddy field in 2013 and 2014 (**a**) and export loads of total P and PO_4^{3-}–P (**b**)

an average of 56.9%. Phosphate was the main form of total P runoff pollution in the surface runoff.

Suggestions on reducing runoff pollution

When there was less precipitation, there was a tendency of excessive irrigation in paddy fields for extensive agricultural water management. To avoid unnecessary runoff, in practice of paddy field management, the irrigation water volume was suggested to be controlled and the degree of fine management should be improved. Compared to the irrigation volume control, the runoff pollution loads were predominantly governed by the fertilization rate. Therefore, reasonably controlling the fertilizer application rate was more important for reducing surface runoff pollution of paddy fields in the Taihu Lake basin.

The N and P fertilizer application rates were approximately 220–400 kg ha^{-1} and 10–60 kg ha^{-1}, respectively, in farmers' fertilizer practice in intensive rice cropping systems in the Taihu Lake basin (Jiao et al. 2018; Peng et al. 2015, 2011; Wang et al. 2014; Zhao et al. 2012b). The rice N demand and recommended fertilizer N supply were 100–150 kg ha^{-1} and 150–200 kg ha^{-1}, respectively, for paddy fields in irrigation rice–wheat systems (Spiertz 2010). The recommended fertilizer N application rate was 210 kg ha^{-1} for paddy fields in the Taihu Lake basin (Jiang et al. 2012). In the Taihu Lake basin, the threshold and optimal N fertilizer supply rate were 180 kg ha^{-1} and 200 kg ha^{-1}, respectively (Jiao et al. 2018), which was in accordance with the suggested fertilizer application rate in most areas in China (Xu et al. 2017). The optimal P fertilizer rate of paddy fields was 10–45 kg ha^{-1} in the Taihu Lake basin (Wang et al. 2014). As analysed, the recommended fertilizer N application rate was approximately 200 kg ha^{-1} and the recommended fertilizer P application rate was less than 45 kg ha^{-1}. Both the fertilizer N and P rate of the paddy field exceeded the optimal application rate during the study period. Therefore, the mean reduction potential of N and P fertilization was 38.9 kg ha^{-1} and 7.5 kg ha^{-1}, respectively.

Conclusions

In this paper, the "water balance method" was implemented to analyse the water balance and the N and P runoff loads of the paddy field for 2 years. The total inflow difference in the paddy field between the 2 years was 22.5% with more irrigation and less precipitation. There was a tendency of excessive irrigation due to less precipitation in paddy fields for extensive agricultural water management. Precipitation and artificial drainage led to most of the surface runoff, but the irrigation return flow should not be neglected in paddy fields in situ. More than half of the irrigation cases would occur as irrigation return flow, which accounted for an average of 11.8% of the irrigation. In practice of paddy field management, the irrigation water volume is suggested to be controlled and the degree of fine management should be improved. The variation in N and P concentrations in the surface runoff of the paddy field was predominantly governed by the times of fertilization. Compared to the irrigation volume control, the runoff pollution loads were predominantly governed by the fertilization rate. The mean reduction potential of N and P fertilization was 38.9 kg ha^{-1} and 7.5 kg ha^{-1}, respectively. Reasonably controlling the fertilizer application rate was more important for reducing surface runoff pollution of paddy fields. For the problem of excessive irrigation and excessive fertilization, how to fertilizer and irrigate paddy fields scientifically and reasonably needs to be further studied to improve the surface runoff pollution of paddy fields in the Taihu Lake basin.

References

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. Fao Irrigation & Drainage Paper 56

Belder P et al (2004) Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. Agr Water Manag 65(3):193–210

Bouman BAM, Wopereis MCS, Kropff MJ, Berge HFMT, Tuong TP (1994) Water use efficiency of flooded rice fields II. Percolation and seepage losses. Agr Water Manag 26(4):291–304

Bouman BAM, Humphreys E, Tuong TP, Barker R (2007a) Rice and Water. Adv Agron 92(04):187–237

Bouman M, Lampayan RM, Tuong TP (2007b) Water management in irrigated rice: coping with water scarcity, vol 54. International Rice Research Institute, Los Banos

Cao Y, Yin B (2015) Effects of integrated high-efficiency practice versus conventional practice on rice yield and N fate. Agr Ecosyst Environ 202:1–7

Chen QH et al (2016) Characteristics of nitrogen and phosphorus runoff losses in organic and conventional rice-wheat rotation farmland in Taihu Lake Region. J Ago-Environ Sci 35(8):1550–1558 **(in Chinese with English abstract)**

Choi JD, Park WJ, Park KW, Lim KJ (2013) Feasibility of SRI methods for reduction of irrigation and NPS pollution in Korea. Paddy Water Environ, 11(1–4):241–248

Guo L (2007) Doing battle with the green monster of Taihu Lake. Science 317(5842):1166

Guo HY, Wang XR, Zhu JG (2004) Quantification and index of nonpoint source pollution in Taihu Lake region with GIS. Environ Geochem Health 26(2):147–156

Guo JH et al (2010) Significant acidification in major Chinese croplands. Science 327(5968):1008–1010

Huang HC, Liu CW, Chen SK, Chen JS (2003) Analysis of percolation and seepage through paddy bunds. J Hydrol 284(1):13–25

Huang DF, Li WH, Wang LM, Lin XJ, Fan P, Qiu XX (2013) Effects of water and fertilizer managements on yield, nutrition uptake of rice and loss of nitrogen and phosphorus by runoff from paddy field. J Soil Water Conserv 27(02):62–66 **(in Chinese with English abstract)**

Huang NB, Su BL, Li RR, Yang WZ, Shen MM (2014) A field-scale observation method for non-point source pollution of paddy fields. Agr Water Manage 146:305–313

Inthavong T, Tsubo M, Fukai S (2011) A water balance model for characterization of length of growing period and water stress development for rainfed lowland rice. Field Crops Res 121(2):291–301

Jia GH, Yan JZ, Wang YY, Zhu FW (2013) Field test and research on agricultural water-saving irrigation and pollution reduction in Taihu Lake Basin. Yangtze River 44(3):81–84 **(in Chinese with English abstract)**

Jiang XS, Liu CL, Sui B, Dong CX, Guo SW (2012) Problems and proposals of the current fertilization situation in the rice-wheat rotation system in Tai Lake basin. Chin Agric Sci Bull 28(15):15–18 **(in Chinese with English abstract)**

Jiao JG et al (2018) Assessing of an irrigation and fertilization practice for improving rice production in the Taihu Lake region (China). Agr Water Manag 201:91–98

Jin SK, Oh SY, Oh KY (2006) Nutrient runoff from a Korean rice paddy watershed during multiple storm events in the growing season. J Hydrol 327(1):128–139

Khepar SD, Yadav AK, Sondhi SK, Siag M (2000) Water balance model for paddy fields under intermittent irrigation practices. Irrig Sci 19(4):199–208

Kim HK, Jang TI, Im SJ, Park SW (2009) Estimation of irrigation return flow from paddy fields considering the soil moisture. Agr Water Manag 96(5):875–882

Ladha JK, Krupnik TJ, Six J, Kessel CV, Pathak H (2005) Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. Adv Agron 87:85–156

Lin L, Zhang ZB, Janssen M, Lennartz B (2014) Infiltration properties of paddy fields under intermittent irrigation. Paddy Water Environ, 12(1):17–24

Liu YL, Zhou ZQ, Zhang XX, Xu X, Chen H, Xiong ZQ (2015) Net global warming potential and greenhouse gas intensity from the double rice system with integrated soil-crop system management: a three-year field study. Atmos Environ 116:92–101

Ongley ED, Xiaolan Z, Tao Y (2010) Current status of agricultural and rural non-point source pollution assessment in China. Environ Pollut 158(5):1159–1168

Peng SZ, Yang SH, Xu JZ, Luo YF, Hou HJ (2011) Nitrogen and phosphorus leaching losses from paddy fields with different water and nitrogen managements. Paddy Water Environ, 9(3):333–342

Peng SZ, He YP, Yang SH, Xu JZ (2015) Effect of controlled irrigation and drainage on nitrogen leaching losses from paddy fields. Paddy Water Environ, 13(4):1–10

Reidsma P et al (2012) Integrated assessment of agricultural land use policies on nutrient pollution and sustainable development in Taihu Basin, China. Environ Sci Policy 18(4):66–76

Rijsberman FR (2006) Water scarcity: fact or fiction? Agr Water Manag 79(1):5–22

Spiertz JHJ (2010) Nitrogen, sustainable agriculture and food security. A review. Agron Sustain Dev 30(1):43–55

Sun YJ et al (2012) The effects of different water and nitrogen managements on yield and nitrogen use efficiency in hybrid rice of China. Field Crops Res 127:85–98

Tan XZ, Shao Du, Liu HH, Yang FS, Xiao C, Yang HD (2013) Effects of alternate wetting and drying irrigation on percolation and nitrogen leaching in paddy fields. Paddy Water Environ, 11(1–4):381–395

Tan XZ, Shao DG, Liu HH (2014) Simulating soil water regime in lowland paddy fields under different water managements using HYDRUS-1D. Agr Water Manag 132(2):69–78

Tan XZ, Shao DG, Gu WQ, Liu HH (2015) Field analysis of water and nitrogen fate in lowland paddy fields under different water managements using HYDRUS-1D. Agr Water Manag 150:67–80

Tian YH, Yin B, Yang LZ, Yin SX, Zhu ZL (2007) Nitrogen runoff and leaching losses during rice-wheat rotations in Taihu Lake region, China. Pedosphere 17(4):445–456

Tsubo M, Shu F, Basnayake J, Tuong TP, Bouman B, Harnpichitvitaya D (2005) Estimating percolation and lateral water flow on sloping land in rainfed lowland rice ecosystem. Plant Prod Sci 8(3):354–357

Vitousek PM et al (2009) Nutrient imbalances in agricultural development. Science 324(5934):1519–1520

Vitousek PM, Porder S, Houlton BZ, Chadwick OA (2010) Terrestrial phosphorus limitation: mechanisms, implications, and nitrogen–phosphorus interactions. Ecol Appl 20(1):5–15

Wang HL, Sun ZZ, Li XY, Du XZ, Li WZ (2013a) Comparison and selection among nonpoint pollution models. Environ Sci Technol 36(5):176–182 **(in Chinese with English abstract)**

Wang WL, Liang T, Wang LQ, Liu YF, Wang YZ (2013b) The effects of fertilizer applications on runoff loss of phosphorus. Environ Earth Sci 68(5):1313–1319

Wang J, Wang DJ, Zhang G, Wang Y, Wang C, Teng Y, Christie P (2014) Nitrogen and phosphorus leaching losses from intensively managed paddy fields with straw retention. Agr Water Manag 141:66–73

Wu D (2015) Drainage processes and the lateral drainage effect of the main ditches on the paddy fields in the Plain River Network Regain. Xi'an University of Technology

Xu XP, He P, Yang FQ, Ma JC, Pampolino MF, Johnston AM, Zhou W (2017) Methodology of fertilizer recommendation based on yield response and agronomic efficiency for rice in China. Field Crops Res 206:33–42

Yao FX et al (2012) Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation. Field Crops Res 126(1):16–22

Ye Y, Liang X, Chen Y, Liu J, Gu J, Guo R, Li L (2013) Alternate wetting and drying irrigation and controlled-release nitrogen fertilizer in late-season rice. Effects on dry matter accumulation, yield, water and nitrogen use. Field Crops Res 144(6):212–224

Zhang HJ, Chen F (2010) Non-point pollution statistics and control measures in Taihu Basin. Water Resour Prot 26(3):87–90 **(in Chinese with English abstract)**

Zhao X, Xie YX, Xiong ZQ, Yan XY, Xing GX, Zhu ZL (2009) Nitrogen fate and environmental consequence in paddy soil under rice-wheat rotation in the Taihu lake region, China. Plant Soil 319(1–2):225–234

Zhao X, Zhou Y, Min J, Wang S, Shi W, Xing G (2012a) Nitrogen runoff dominates water nitrogen pollution from rice-wheat rotation in the Taihu Lake region of China. Agr Ecosyst Environ 156(4):1–11

Zhao X, Zhou Y, Wang SQ, Xing GX, Shi WM, Xu RK, Zhu ZL (2012b) Nitrogen balance in a highly fertilized rice-wheat double-cropping system in Southern China. Soil Sci Soc Am J 76(3):1068

Zhou JW, Su BL, Huang NB, Guan YT, Zhao K (2016) Runoff pollution experiments of paddy fields under different irrigation patterns. Environ Sci 36(4):1145–1152 **(in Chinese with English abstract)**