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RESEARCH ARTICLE

DITCHES AND PONDS CAN BE THE SOURCES OR SINKS OF NON-POINT SOURCE POLLUTION: OBSERVATIONS IN AN UPLAND AREA IN THE JINGLINXI CATCHMENT, CHINA

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KEYWORDS

ditches, ponds, non-point source pollution, mountainous areas, nitrogen, phosphorus

HIGHLIGHTS

- The source and sink status of ditches and ponds was studied in an upland area in the Jinglinxi catchment, China.
- Over the past 15 years, ditch length has increased by 32% and small pond number by 75%.
- Ditches and ponds are important nutrient sinks in the dry season.
- Retention of nutrients in ditches and ponds is up to 20%.

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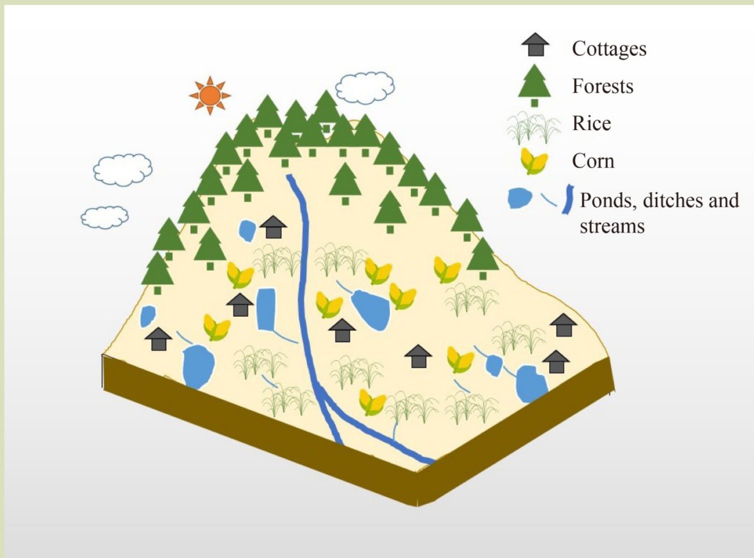
GRAPHICAL ABSTRACT



ABSTRACT

As the common features of agroecosystems, ditches and ponds benefit the irrigation and drainage, as well as intercepting non-point source pollutants. However, most ditch-pond studies have been conducted in lowland areas. To test this source-sink assumption in upland areas, this study made observations on the ecological function of the ditch and pond system in a typical catchment in China. First, the changes in ponds in the catchment were analyzed using high-resolution remote sensing data. Then, the migration of agricultural pollutants in ditches and ponds were analyzed by field sampling and laboratory detection. The results showed that over the past 15 years the length of ditches in the catchment and the number of small ponds (< 500 m^2) have increased by 32% and 75%, respectively. The rate of change in nutrient concentrations in the ditches and ponds were mostly from −20% to 20%, indicating ditches and ponds can be both sources and sinks for agricultural pollutants. Lastly, the contributing factors were explored and it was found that ditches and ponds are important sinks in dry season. However, during the rainy season, ditches and ponds become sources of pollutants, with the rapid drainage of ditches and the overflow of ponds in upland areas. The results of this study revealed that the ditches and ponds could be used for ecological engineering in upland catchments to balance drainage and intercept pollutants.

1 INTRODUCTION

Globally, non-point source pollution is an important source of water quality deterioration in rivers and lakes. Agricultural non-point source pollution from rural domestic wastewater and agricultural runoff discharges excess nitrogen and phosphorus compounds into the surrounding water bodies following rainfall, leading to eutrophication in water bodies, lakes and reservoirs[1,2]. Agricultural non-point source pollution restricts the sustainable development of water resources and agriculture all over the world, but is a challenging to study in a whole basin water environment[3]. According to China's Second National Pollution Source Census Bulletin, the total nitrogen emissions from agricultural sources reached 1.4 Mt, accounting for 46.5% of the total emissions.

Ditches and ponds are common in agricultural areas in most countries[4,5]. Ditches are the channels for agricultural drainage to enter rivers or lakes, serving in the provision of both drainage and water purification. Ponds are small bodies standing water and may be permanent or seasonal, man-made or natural, and are generally regarded as temporary reservoirs[6]. A ditch-pond system, consisting of ditches and ponds, is considered to be similar to free-surface wetlands, linking pollution sources to the receiving water bodies[1]. The ditch-pond system includes vegetation, microorganisms and sediment, which can slow down the flow velocity and promote the precipitation of particulate matter carried by running water. At the same time, ditch and pond systems reduces nitrogen and phosphorus concentrations, and those of other nutrients entering the downstream water by means of plant absorption, sediment adsorption and microbial degradation, so as to reduce agricultural non-point source pollution[7]. At present, the use of agricultural ditch and pond systems as an effective method of water treatment to improve water quality has been widely used[8]. As a long-established agricultural system, the function of ditch and pond systems is to reduce drought and flood, provide irrigation water and promote compound agricultural production[9]. Ditch and pond systems are not only important in many agricultural irrigation systems, but also in runoff interception, nutrient storage, water recycling and sediment promotion[10]. This system can significantly reduce the flow velocity, increase the residence time of water and increase the deposition and interception of particulate matter[11,12].

In China, the Three Gorges Reservoir area is mountainous and hilly, upland landscape with high population density[13]. Sloping farmland is the source of soil and water loss in hilly areas. In the upper reaches of the Yangtze River, 60% of the total soil erosion comes from sloping farmland[14]. The utilization intensity of cultivated land in hilly areas is high and the loss of nitrogen and phosphorus in the surface layer of cultivated land is serious, which makes the eutrophication of water bodies in the region become increasingly serious, and the problems of water environment become increasingly prominent. As an important farming area in southern China, the Three Gorges Reservoir area covers a wide area of hills and serious soil erosion, which further exacerbates the problem of agricultural non-point source pollution[15]. In China, ponds are mainly distributed in the eastern and southern regions. In the mountainous and hilly areas with abundant precipitation in the south, ditches and ponds can receive rainfall and runoff, and serve important functions in environmental protection and management[5,16]. However, most of the studies on ditches and ponds have been conducted in the lowland areas, and there are few studies with field observations in upland areas[17,18].

In this study, field monitoring and sample analysis of catchment in upland areas was conducted over 2 years using high-resolution remote sensing satellite images to explore whether ditches and ponds can be used for ecological engineering in a representative agricultural catchment. The main objectives of this study were: (1) to explore changes of ponds and ditches in the catchment; (2) to explain the spatial distribution of ponds and ditches; and (3) to determine if ditches and ponds are sources or sinks of agricultural non-point source pollutants.

2 MATERIALS AND METHODS

2.1 Study area

The ditch and pond systems studied are located in Jinglinxi catchment (31.186° to 31.273° N, 108.335° to 108.375° E), which is a typical hilly, agrarian catchment located the north of the Three Gorges Reservoir area, China (Fig. 1). The area of the catchment is 9.51 km^2, and the main land uses are woodland (39.2%), dry farmland (30.0%), paddy land (24.8%) and residential land (10.0%). The elevations range from 665 to 1117 m. The overall elevation difference of the catchment is large, but the central part is relatively flat, so it is suitable for agricultural cultivation. The average annual precipitation in the catchment is 1293 mm, and the seasonal distribution of precipitation is uneven, with the precipitation from May to September accountings for about 66% of the annual precipitation. The catchment is mostly terraced, with upslope unirrigated fields mostly used for maize production and paddies in the valley used for rice production. Abundant artificial ditches and ponds have been built in the catchment, which are helpful for irrigation and drainage of paddies. The ditches are distributed in a reticulated pattern throughout the catchment, especially in the middle and lower reaches where the farmland is concentrated. Ponds have relatively scattered distribution, with a large number in the southern part of the catchment. Most of the ponds are distributed around paddies for irrigation and aquaculture. The ditch and pond systems in this catchment is well-established and mature. Therefore, this study selected this area as a case study for research on reducing agricultural non-point source pollution using ditch and pond systems.

The land use in the Jinglinxi catchment includes unirrigated fields, paddies, woodland, residential land and ponds (Fig. 2). Among them, unirrigated fields and paddies occupy the largest area, accounting for 57.7% and 33.6% of the catchment area, respectively. Unirrigated fields and paddies are mainly distributed in the middle and south of the catchment. The main crops grown in the unirrigated fields are maize and vegetables. Woodlands are mainly distributed in the northern part of the catchment with steep slopes that cannot be used for crop production. The land use in Jinglinxi catchment is detailed in Table 1.

2.2 Data collection and field investigation

Meteorological, hydrological and water quality data were

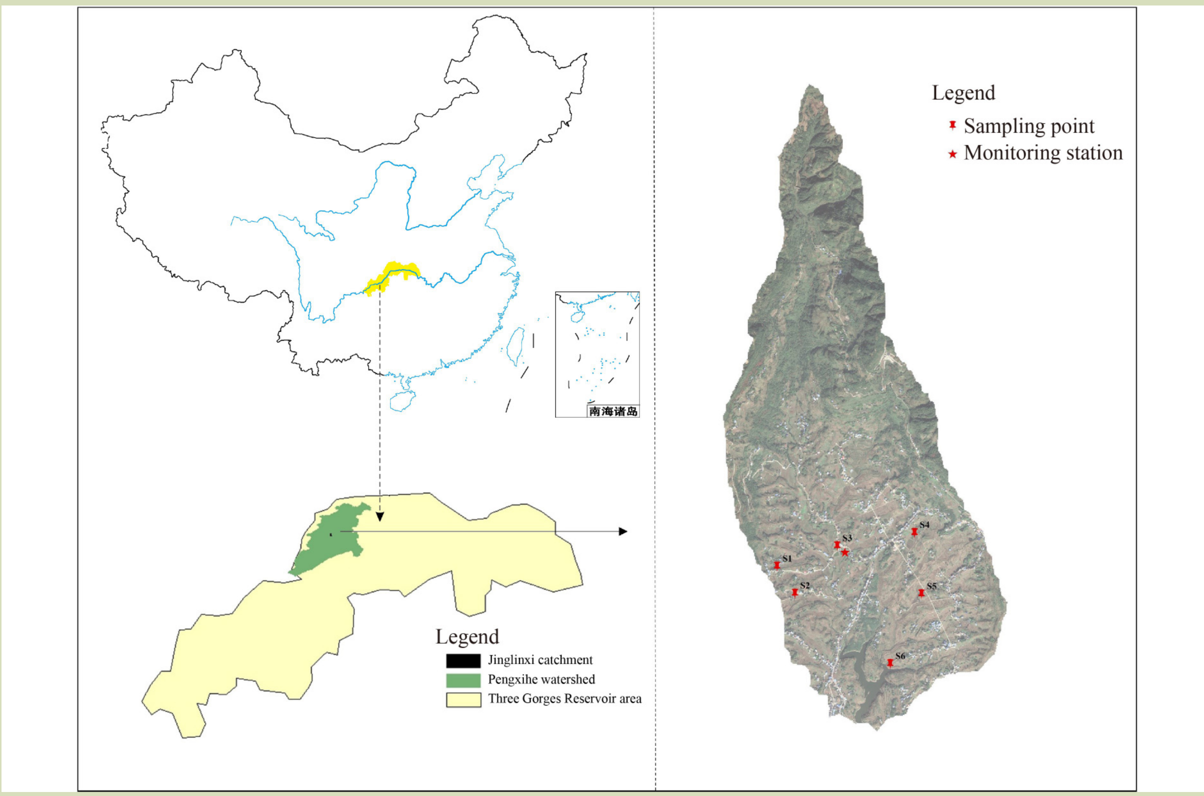


Fig. 1 Location of Jinglinxi catchment and distribution of sampling points (审图号: GS 京 (2023) 2266 号).

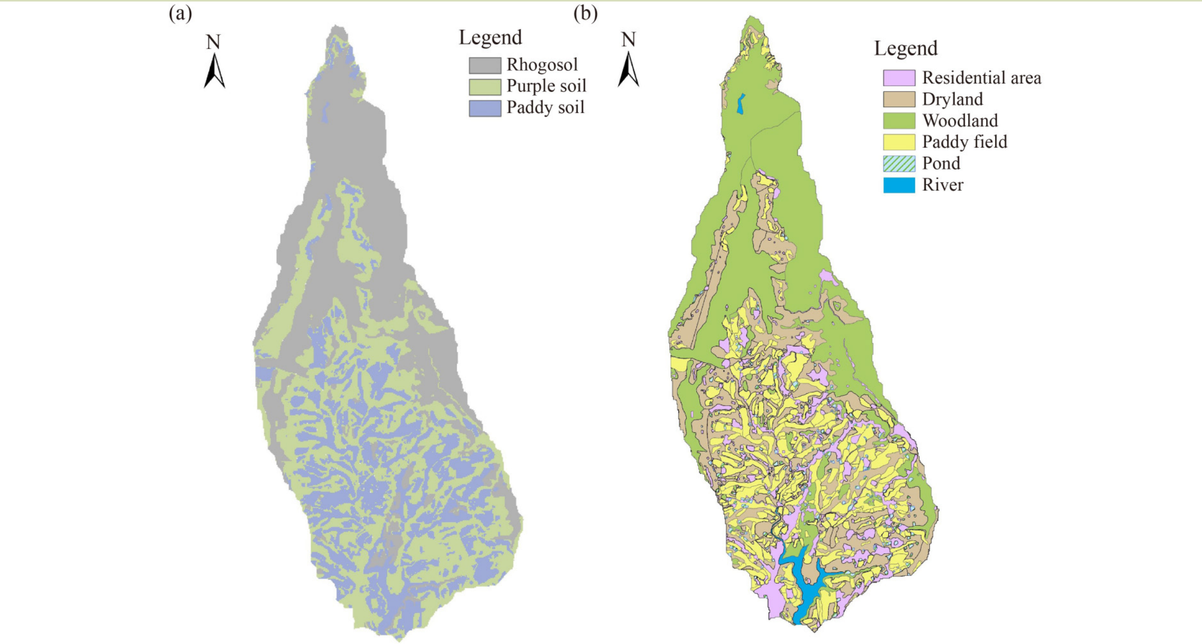


Fig. 2 Soil types (a) and land use (b) in Jinglinxi catchment (审图号: GS 京 (2023) 2266 号).

Table 1 Soil types and main land use in Jinglinxi catchment

Soil type	Area (km^2)	Proportion (%)	Land use	Area (ha)	Proportion (%)
Purple soil	3.54	37.12	Paddies	319.536	33.60
Rhogosol	3.49	36.55	Unirrigated fields	548.727	57.70
Paddy soil	2.51	26.33	Woodland	17.4984	1.84

collected for this study. Basic data were: digital elevation model (DEM) for the study area, remote sensing data and the daily rainfall data of 2020–2022. The ditch and pond distribution was based on the field investigations and remote sensing maps. DEM with 30 m × 30 m resolution was obtained from the Chinese Academy of Sciences Data. Remote sensing data (1:5000) from both 2009 and 2019 were derived from Google Maps. Land use were based on local information and visual interpretation of the remote sensing data, and a land use map with 2 m × 2 m resolution. Daily rainfall data were obtained for 2010 to 2020 from the local meteorological bureau. In addition, detailed information on the distribution of ditches and ponds was obtained from a field investigation conducted in September and December 2020. Given the small size of many ponds, these is easily overlooked this kind of landscape. In this study, we use high-resolution remote sensing images, with the help of draw tools in ArcGIS software. Combining remote sensing images, with field investigations, the spatial distribution map of ditches and ponds in Jinglinxi catchment was constructed for 2009 and 2019.

2.3 Field sampling and measurements

We selected a total of six sampling sites in the study area, including four ditch/pond combinations (S1, S2, S4 and S5), sampling points near catchment monitoring stations (S3) and outlet sampling sites (S6) (Fig. 1). The pond is connected to the nearby farmland through ditches. According to the actual distribution of local ditches and ponds, the types of land use around the ditches and ponds (woodland and paddies) and ditches of different materials (soil and concrete), four representative ditches and ponds were selected to set up sampling points (Table 2). The details of each sampling point are described below. Water samples were collected in polyethylene bottles at inlet and outlet of ditches and ponds, and at the middle and outlet of the catchment at each sampling site. The collected samples are taken to the laboratory for analysis. Water samples were collected from 2020 to 2022. The

Table 2 Type and location of the six sampling points monitored in this study

Number	Description	Latitude (° N)	Longitude (° E)
S1	Woodland-ditch	31.2278	108.3412
S2	Paddy-ditch-pond	31.2252	108.3428
S3	Monitoring station	31.2292	108.3479
S4	Ditch	31.2302	108.3558
S5	Ditches made of soil and concrete	31.2253	108.3563
S6	Outlet	31.2188	108.3527

monitoring indexes of water samples were total nitrogen (TN), total phosphorus (TP), dissolved phosphorus (DP) and the particulate phosphorus (PP), and the analysis method was based on "Monitoring and Analysis Method of Water and Waste Water." After collecting the water sample, if the water sample was not analyzed on the same day, it should be immediately frozen and kept frozen until analyzed.

S1: Woodland-ditch-pond combination. This point was located below a woodland with a steep slope, with no nearby domestic sewage discharge. The ditch was made of soil, next to the ditch was sloping farmland, and the ditch outlet was connected to the farmland. The ditch was 20 m long, 50 cm wide, and 55 cm deep.

S2: Paddy-ditch-pond combination. This point was located near gently sloping farmland, with no nearby domestic sewage discharge. The ditch was made of soil, next to the ditch was paddy and sloping farmland, and the ditch outlet was connected to a paddy. The ditch was 30 m long, 60 cm wide, and 50 cm deep.

S3: Long ditch. This point was located near gently slope farmland and adjacent to a pond. The ditch was 75 m long, 55 cm wide and 60 cm deep. Under heavy rainfall, the water in the pond could overflow into the ditch. There was no nearby domestic sewage discharge. The ditch material was made from concrete, and contained sediment. The ditch inlet and outlet were connected to a paddy, but not connected to the adjacent pond or sloping farmland.

S4: Ditch-pond (soil and concrete ditches) combination. This point was located near the sloping farmland with a steep slope, with no obvious nearby domestic sewage discharge. The water intakes of the two ditches of different materials were connected to a pond, with the two ditches separated by sloping farmland, the soil ditch on the low side and the concrete ditch on the high side. The soil ditch was 30 m long, 55 cm wide and 50 cm deep, and the concrete trench is 57 m long, 60 cm wide and 50 cm deep.

2.4 Chemical analysis

The TN in the sample was measured by alkaline potassium persulfate digestion ultraviolet spectrophotometry and the TP concentration was measured by ammonium molybdate spectrophotometry. The DP in the sample were measured by the same test method as TP after the sample was filtered through 0.45 μm filter membrane. The PP were obtained from the differences between TP and DP.

2.5 Data calculation and statistical analysis

In this study, Origin 2021 was used for mapping, SPSS 18.0 was used for data processing and statistical analysis. The spatial distribution of sampling points, ditches and ponds was plotted using ArcMap 10.2, and the rest of the data was plotted using Origin 2021.

Pollutant concentration change rate was used to evaluate the effect of ditch and pond system on TN, TP, DP and PP. The pollutant concentration change rate was calculated as:

$$R_c = \frac{C_{in} - C_{out}}{C_{in}} \times 100\%$$

where, R_c is pollutant concentration change rate (%); C_{in} is the concentration of pollutants of runoff in the inlet (mg·L^{-1}); and C_{out} is the concentration of pollutants of runoff in the outlet, (mg·L^{-1}).

3 RESULTS

3.1 Changes in ditches and ponds from 2009 to 2019

In 2009, the total length of ditches in the study catchment was about 26 km. In 2019, the total length of ditches was about 35 km. The length of ditches in 2019 increased by 31.8% compared with 2009. The average depth of the ditch was about 40 cm wide and about 35 cm deep. From 2009 to 2019, the density of ditches increased, especially in the southern part of the catchment. The ponds were scattered, mostly in the southern part of the catchment. According to the field observations, most of the ponds appeared to be for both aquaculture and irrigation. Some of the ponds were distributed among paddies and had been converted from the paddies mostly for fish culture. Other ponds were distributed between the upslope fields and the paddies below the slope. These ponds collected rainfall and slope runoff during the rainy season and were used to irrigate the paddies in the dry season.

From 2009 to 2019, the number and area of ponds in the catchment increased significantly, and the distribution density of ponds increased from 14 to 22 ponds km^{-2}. In 2009 and 2019, there were 136 and 210 ponds respectively (Table 3 and Fig. 3). The volume and area of the ponds increased from 2.35×10^5 to 3.44×10^5 m^3, and from 9.39 to 13.7 ha (Table 3). The number of ponds increased by 54%, and the number of ponds smaller than 500 m^2 increased by 75%. The newly built ponds were mainly concentrated in the areas with frequent agricultural activities in the middle of the catchment, and were mostly converted paddies used to raise fish. In the study area, many new ponds were built between 2009 and 2019, and many ditches were built to connect the ponds to farmland. The newly built ditches were distributed throughout the catchment, especially in the lower reaches where there were more farmlands. In addition, after on-site investigation, we found that compared with 2009, many new roads had been built in the lower reaches of the catchment, and corresponding ditches had been built on both sides of the roads. The newly built roadside ditches can effectively prevent the collapse of fertile fields caused by landslides and floods in the catchment.

3.2 Variation in nitrogen and phosphorus concentrations in the catchment

In general, as evident in Fig. 4(a, b), the concentrations of nitrogen and phosphorus changed with time. The concentrations of nitrogen and phosphorus in the rainy season was higher than that in dry season. Other studies have shown that rainfall is the driving factor of non-point source pollution in a catchment, and rainfall, rainfall intensity and temporal and spatial distribution are decisive factors in the loss of non-point source pollutants[19]. In Jinglinxi catchment, summer and autumn (May to September) is the rainy season, with the rainfall in that period accounting for more than 66% of the total annual rainfall.

In 2020, the average concentrations of nitrogen and phosphorus in rainy season were 1.08 and 0.21 mg·L^{-1} respectively, and in dry season these were 0.86 and 0.15 mg·L^{-1}, respectively. The highest total nitrogen was 3.09 mg·L^{-1} in June and the lowest 0.12 mg·L^{-1} in January (Fig. 4). The highest total phosphorus was 0.84 mg·L^{-1} in October and the lowest 0.05 mg·L^{-1} in February. In 2021, the average concentrations of nitrogen and phosphorus in rainy season were 2.80 and 0.30 mg·L^{-1}, respectively, and those in dry season were 1.60 and 0.15 mg·L^{-1}, respectively. The highest total nitrogen was 7.46 mg·L^{-1} in September, and the lowest 0.001 mg·L^{-1} in March (Fig. 4). The highest total phosphorus was 2.12 mg·L^{-1} in September, and the lowest 0.04 mg·L^{-1} in July. It is likely that this temporal variation of phosphorus concentration was driven by the dilution effect of rainfall. In the rainy season, the runoff increased significantly under the influence of rainfall, and the phosphorus concentration decreased due to the dilution effect of the high flow.

Table 3 Pond classification statistics for 2009 and 2019

Ponds area (m^2)	2009				2019			
	Number	Total length (km)	Total area (ha)	Total capacity (10^4 m^3)	Number	Total length (km)	Total area (ha)	Total capacity (10^4 m^3)
≤ 499	56	4.02	1.79	4.47	98	6.59	2.81	7.03
500–999	50	5.23	3.49	8.73	69	7.23	4.81	12.03
1000–1499	22	3.09	2.75	6.88	30	4.20	3.71	9.27
1500–1999	8	1.33	1.36	3.39	10	1.69	1.70	4.24
> 2000	–	–	–	–	3	0.65	0.71	1.77
Sum	136	13.67	9.39	23.47	210	20.36	13.74	34.35

Note: Dashes indicate data unavailable.

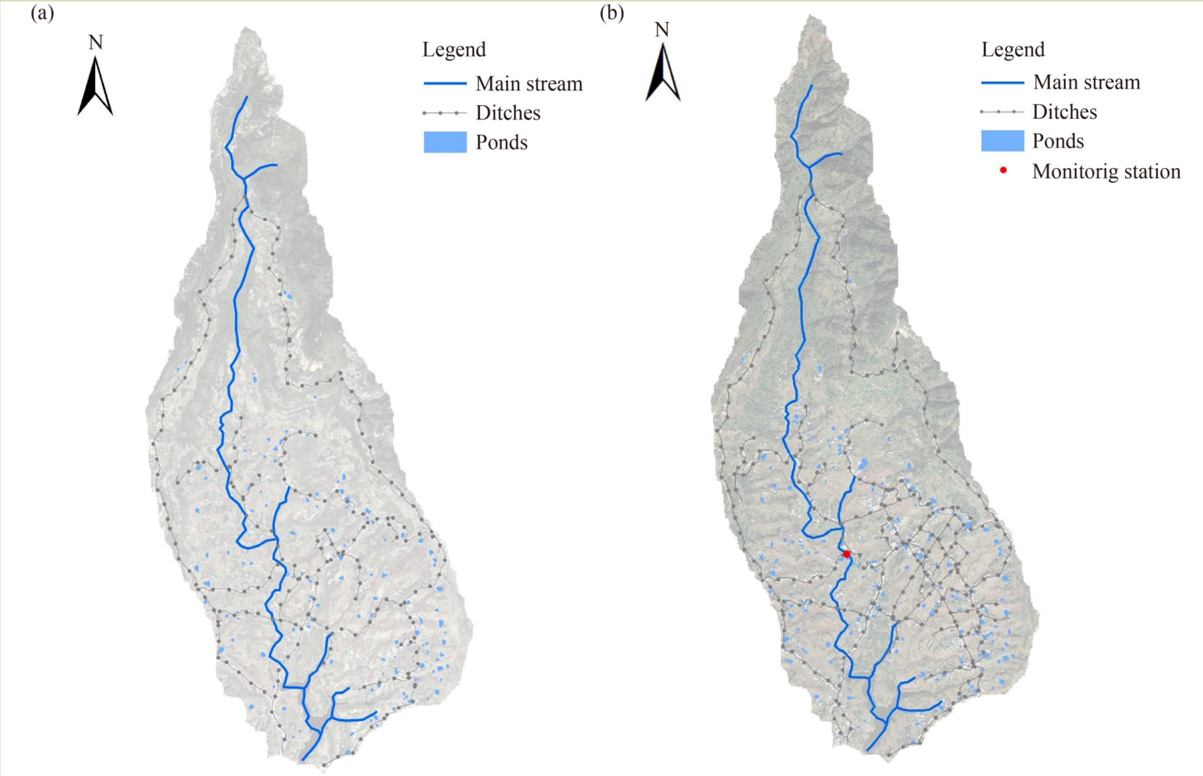


Fig. 3 Spatial distribution of ditches and ponds in 2009 (a) and 2019 (b) (审图号: GS 京 (2023) 2266 号).

In general, as evident in Fig. 4(c, d), nitrogen load varied significantly with rainfall in 2020 and 2021. In 2020, the nitrogen and phosphorus loads were between 0.226 and 117 $kg \cdot d^{-1}$, and 0.115 and 27.1 $kg \cdot d^{-1}$, respectively. In 2021, the daily loads of nitrogen and phosphorus were between 0.001 and 327 $kg \cdot d^{-1}$, and 0.105 and 56.9 $kg \cdot d^{-1}$, respectively. The annual rainfall in 2020 and 2021 was 1867 and 2006 mm, respectively. The driving factor of rainfall partly explained why the daily load of nitrogen and phosphorus in the catchment in 2021 was higher than that in 2020. As evident in Fig. 4(c, d), the daily nitrogen and phosphorus loads in Jinglinxi catchment were the highest from June to September in both years. The slopes of the upland area was steep, and the sloping farmland and paddies accounted for a relatively high proportion of the catchment. The heavy rainfall impacted the surface soil of farmland, which washed nitrogen and phosphorus and other substances from the soil into the surface runoff, and thus into the surrounding water bodies.

Some studies had shown that because phosphorus is easily fixed in the soil, it can easily migrate horizontally with surface erosion caused by runoff from heavy rainfall[20]. In the dry season, a large amount of phosphorus accumulated on the surface and was carried into the river with heavy rainfall and runoff, resulting in a sharp increase in the phosphorus concentration in the water at the beginning of the rainy season (in May). After the erosion of surface phosphorus at the beginning of the rainy season, the phosphorus carried by surface runoff into the water body decreased in the middle and late rainy season (from June to September). At the same time, the change of temperature also affected the microbial activity and biogeochemical rate, which leaded to differences in the water self-purification capacity in different seasons[21]. During the rainy season, the overall water temperature was higher, the activity of microorganisms was enhanced, and phytoplankton such as algae grow rapidly, which consumed nutrients in the water, resulting in a decrease in the concentration of nitrogen and phosphorus[20]. However, in this study, the changes of nitrogen and phosphorus in the catchment did not vary consistently with the changes of rainfall. From field observations, it was found that there were a large quantities of mineral fertilizer applied in Jinglinxi catchment from March to June, and August to October each year. In this study area, March to June was the fertilizer application period for rice and

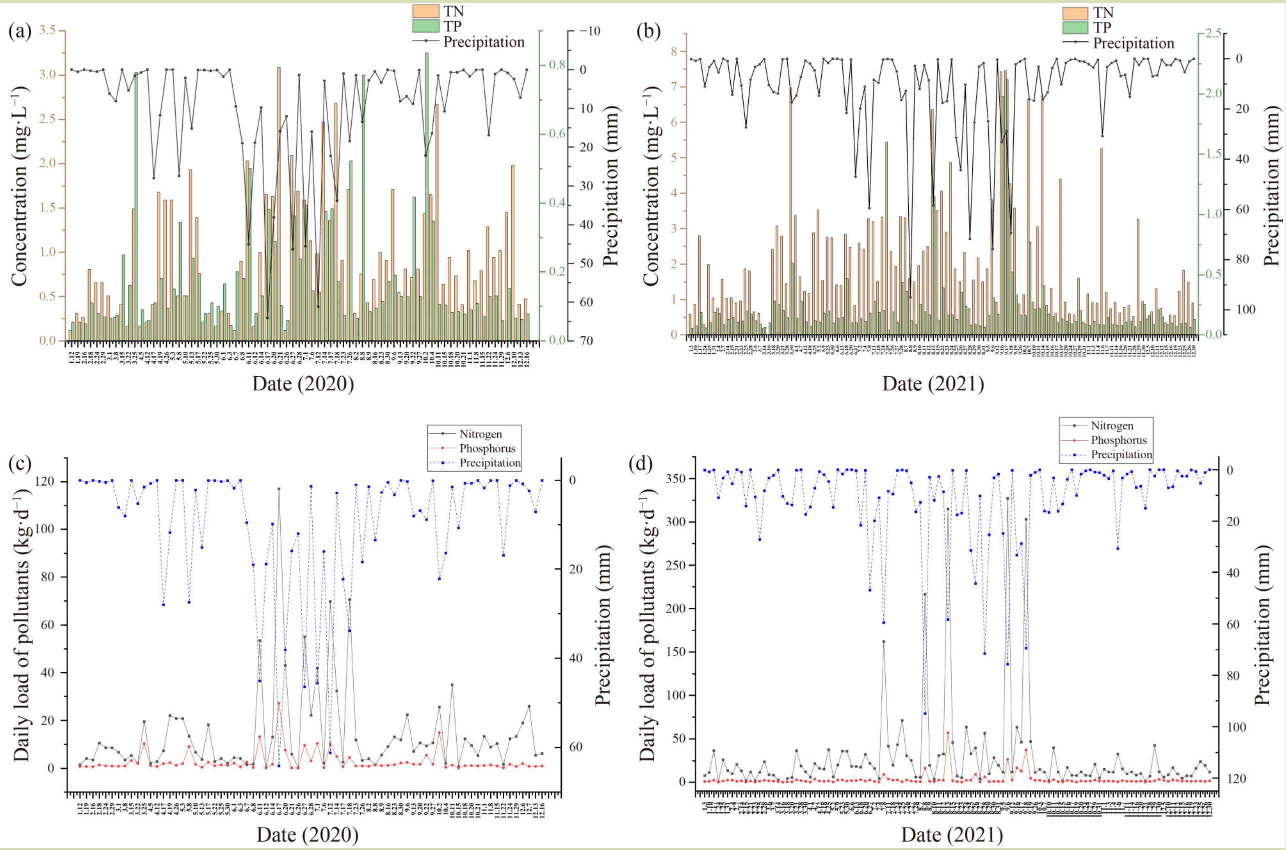


Fig. 4 Changes in nitrogen and phosphorus concentrations in 2020 (a) and 2021 (b), and load in main stream in 2020 (c) and 2021 (d).

maize, and August to October for vegetables. Also, the nitrogen and phosphorus concentrations in runoff increased sharply if it rained soon after fertilizer application. To some extent, this explains the increase of nitrogen and phosphorus concentration in the catchment during the normal period of fertilizer application.

Given the nature of its topography and serious soil erosion, upland areas are some of the serious ecological fragile areas in China. Purple soil is the most important cultivated land resource in south-west China, where the average annual rainfall is high, and the uneven temporal and spatial distribution results in floods and seasonal droughts[22]. Among the soil types in Jinglingxi catchment, purple soil is the highest proportion at about 37%. The important driving factor of non-point source pollution is the runoff caused by rainfall, and the concentration of pollutants during the rainy season is much higher than that in the dry season. The leaching and scouring from rainstorms enable runoff to carry considerable quantities of nutrients and other pollutants, resulting in serious pollution of the receiving water.

3.3 Variation in phosphorus forms in the catchment

Phosphorus migration in runoff mainly included DP and PP. The average concentrations of DP and PP were 0.13 and 0.27 mg·L^{-1} in rainy season, and 0.08 and 0.08 mg·L^{-1} in dry season, respectively. The highest DP was 0.48 mg·L^{-1} in June, and the lowest 0.04 mg·L^{-1} in March. The highest PP was 1.92 mg·L^{-1} in July and the lowest 0 mg·L^{-1} in November. In runoff, PP accounted for up to 96.9% of TP, with an average of 44%.

From the planting period of rice and maize (from March to July) and the planting time of vegetables (from August to February in the next year), the proportion of PP in TP was 40.0% and 46.6%, respectively. In the Jinglinxi catchment (Fig. 2), unirrigated field and paddies were the main land uses. From field observations, it was found that rice crop were grown only once per year, and no other crops were planted in the paddies after rice maturity at the end of August, whereas vegetables were be planted in the unirrigated fields after maize maturity and harvest. Therefore, the amount of fertilizer applied to farmland in the first half of the year was much higher than that in the second half of the year.

Phosphorus is mainly immobilized in the surface soil, so the phosphorus in this soil migrates with erosion caused by surface runoff[23]. Therefore, the amount of phosphorus accumulated in the surface soil is an important factor determining the phosphorus concentration in the runoff. With the sloping terrain of this upland study, and it is understood that most phosphorus loss will occurs with surface erosion as PP. However, in this study, only 44% of phosphorus in the water of the main stream was PP, with 56% being DP. Other studies have shown that the form of phosphorus in the surface water from unfertilized treatments is usually particulate, accounting about 68% of the total phosphorus in the field surface water, with soluble phosphorus accountings for only 32%[24]. In contrast to the unfertilized treatment, in fertilized treatment with soluble phosphate fertilizer, over the first 12 days after application, soluble phosphorus represented 59% of the total phosphorus concentration in the field surface water[24]. Therefore, any drainage of surface water during rice production brings certain risks to the deterioration of surrounding water environment. These results show that phosphorus in surface water mainly comes from applied fertilizers. Since most of the applied phosphorus is soluble phosphorus, DP becomes the main form of phosphorus in surface water.

In contrast to nitrogen, the movement of applied phosphorus in a paddy is limited. After entering the water body, phosphorus is mainly immobilized in the surface soil, and the loss of phosphorus is mainly in particle form under the impact of strong rainfall[25]. When the rainfall coincides with the period of fertilizer application, the phosphorus lost by runoff mainly comes from the application of mineral fertilizer, and the loss form is mostly as DP (Fig. 5). When the periods of rainfall and fertilizer application are staggered, the phosphorus lost in runoff mostly comes from the erosion of soil phosphorus by rainfall, mostly mainly as PP (Fig. 5).

3.4 Overall change of pollutants within ditches and ponds

Figure 6 shows the interception of nitrogen and phosphorus in the ditches and ponds of four sampling sites in a catchment. The change rates for nitrogen and phosphorus concentrations from agricultural non-point source pollutants in ditches and ponds were mostly between −20% and 20%. From all 188 observations, the TN concentration change rate varied greatly

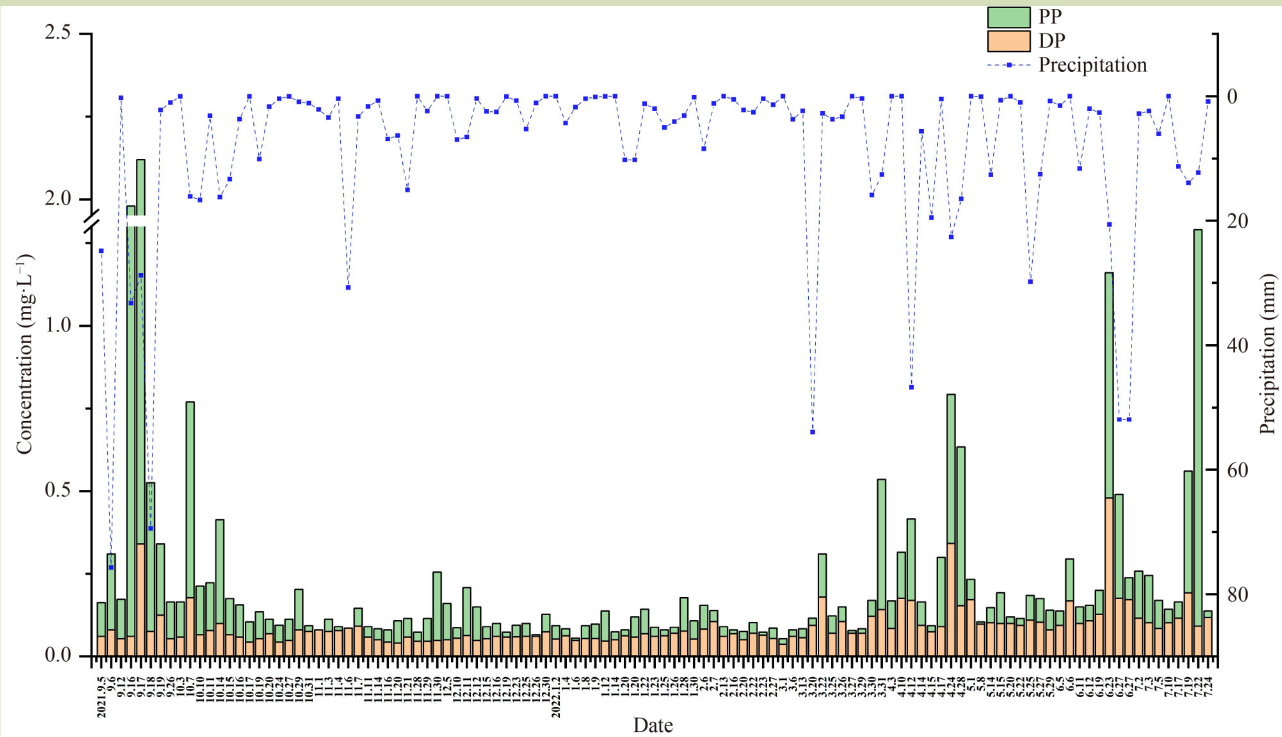


Fig. 5 Concentration changes of different forms of phosphorus in the main stream of the catchment.

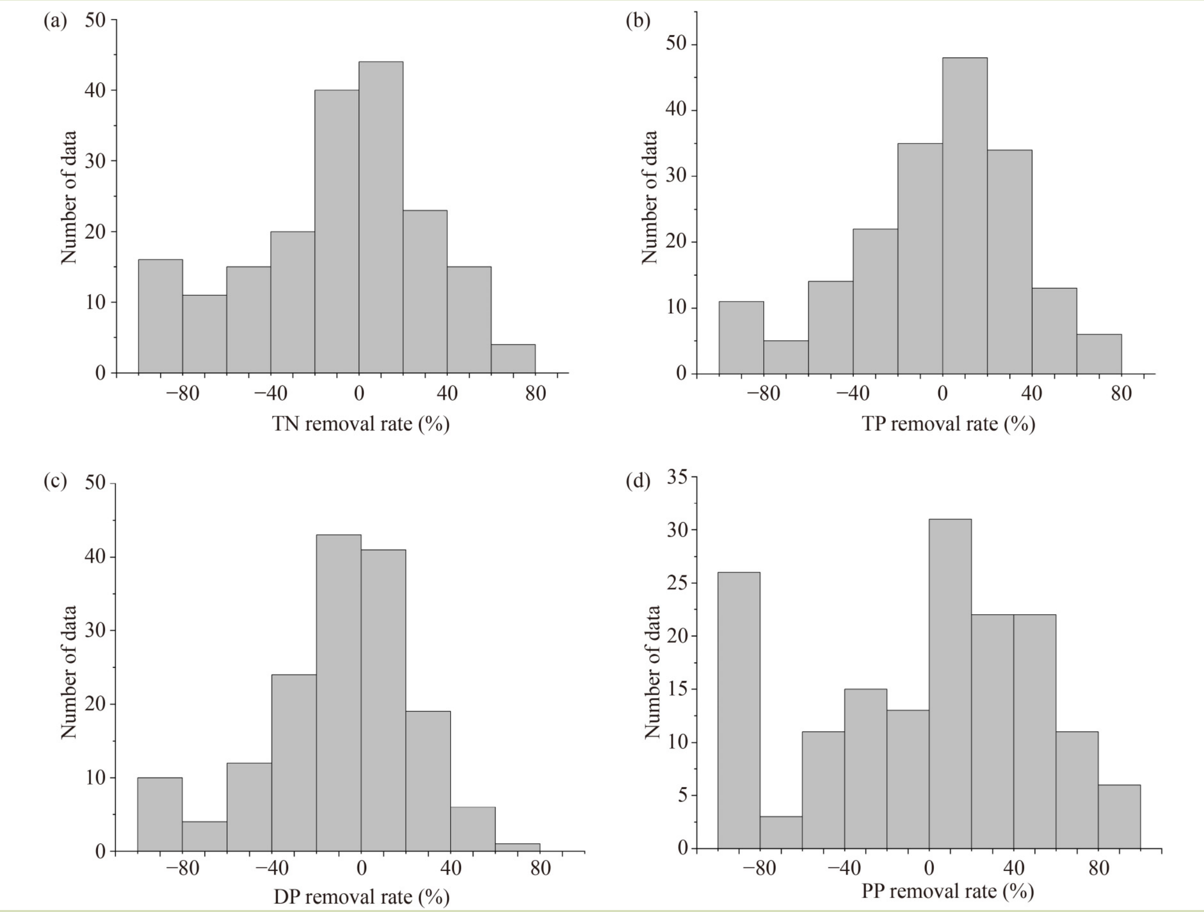


Fig. 6 Overall change rate of nitrogen and phosphorus concentrations in ditches and ponds.

from −781% to 73.6%, with 54.3% being negative rates. The TP concentration change rate varied from −213% to 73.7% with 46.3% being negative rates. Among the 160 observations, the DP change rate varied from −212% to 63.6%, with 58.1% being negative rates. The PP change rate varied from −762% to 100%, with 42.5% being negative rates. This indicate that ditches and ponds become sources rather than sinks under certain circumstances. Some studies have shown that if we gave attention to the impact of single rainfall evens (such as rainstorm) on ditches and ponds, the change rate of nutrient concentrations was more likely to be negative. Continuous rainfall shortening hydraulic retention time, heavy rainfall flushing nutrients out of sediments and fertilizes before rainfall make ditches and ponds more likely to become sources of pollution during such periods.

3.5 Comparison of ditches and ponds between the rainy and dry season

In Jinglinxi catchment, ponds were connected to the nearby farmland through ditches. According to the actual distribution of local ditches and ponds, the types of land use around the ditches and ponds (woodland, paddies and unirrigated fields) and ditches of different materials (soil and concrete), four representative ditch and pond sampling sites were selected in the study area.

S1: Woodland-ditch-pond combination

The change in nutrient concentrations in the woodland-ditch-pond combination is shown in Fig. 7. In general, the inlet water quality in the rainy season was better than that at the outlet, while the water quality at the inlet and outlet were similar in the dry season. Also, in the rainy season, the average concentrations of TN and TP in ponds and ditches were higher than those in the dry season. In the rainy season, nutrients carried by runoff into ditches and rainfall disturbed the bottom mud of ditches, so that the release of nutrients was the main reason the concentration of pollutants in the ditches was higher than that in the ponds. In the dry season, the main reason for the change of pollutant concentration was fertilizer application.

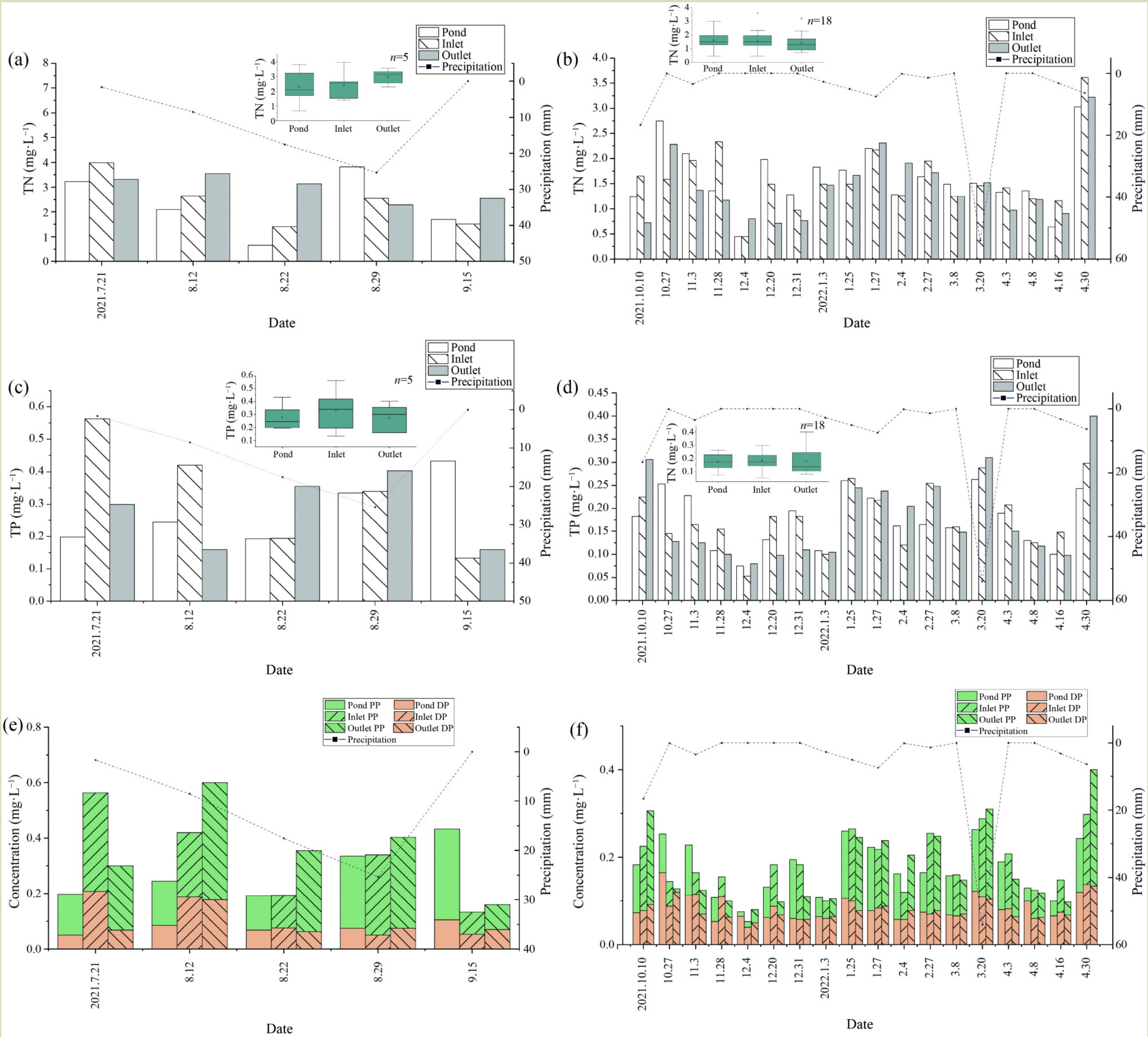


Fig. 7 Changes in nutrient concentration in the woodland -ditch-pond sampling site: total nitrogen (TN) in the rainy (a) and dry (b) seasons, total phosphorus (TP) in the rainy (c) and dry(d) seasons, and combined dissolved and particulate phosphorus (DP and PP) in the rainy (e) and dry (f) seasons.

For example, on 30 April 2022, the concentrations of TN and TP increased significantly, which was due to the fertilizer application at rice transplanting at the end of April and the occurrence of rainfall, resulting in a sharp rise in pollutant concentrations.

As evident in Fig. 7(e,f), most of the phosphorus in the runoff existed as PP in the rainy season, and the greater the rainfall, the greater the proportion of PP to TP in the runoff. Overall, 72.2% of the phosphorus in the inlet of pond and ditch in the dry season was DP, whereas at the ditch outlet, the DP/TP was reduced to 50%. It was clear that in the dry season, the ditch can intercept DP to some degree.

S2: Paddy-ditch-pond combination

The change of nutrient concentration of paddy-ditch-pond combination was shown in Fig. 8. Overall, TN concentrations in the rainy season were higher than in the dry season. The heavy and frequent rainfall in the rainy season scoured the cultivated soil, causing pollutants to enter the ditch in the runoff. At the same time, rainfall scoured the sediments at the bottom of the ditch, releasing pollutants from the sediment and

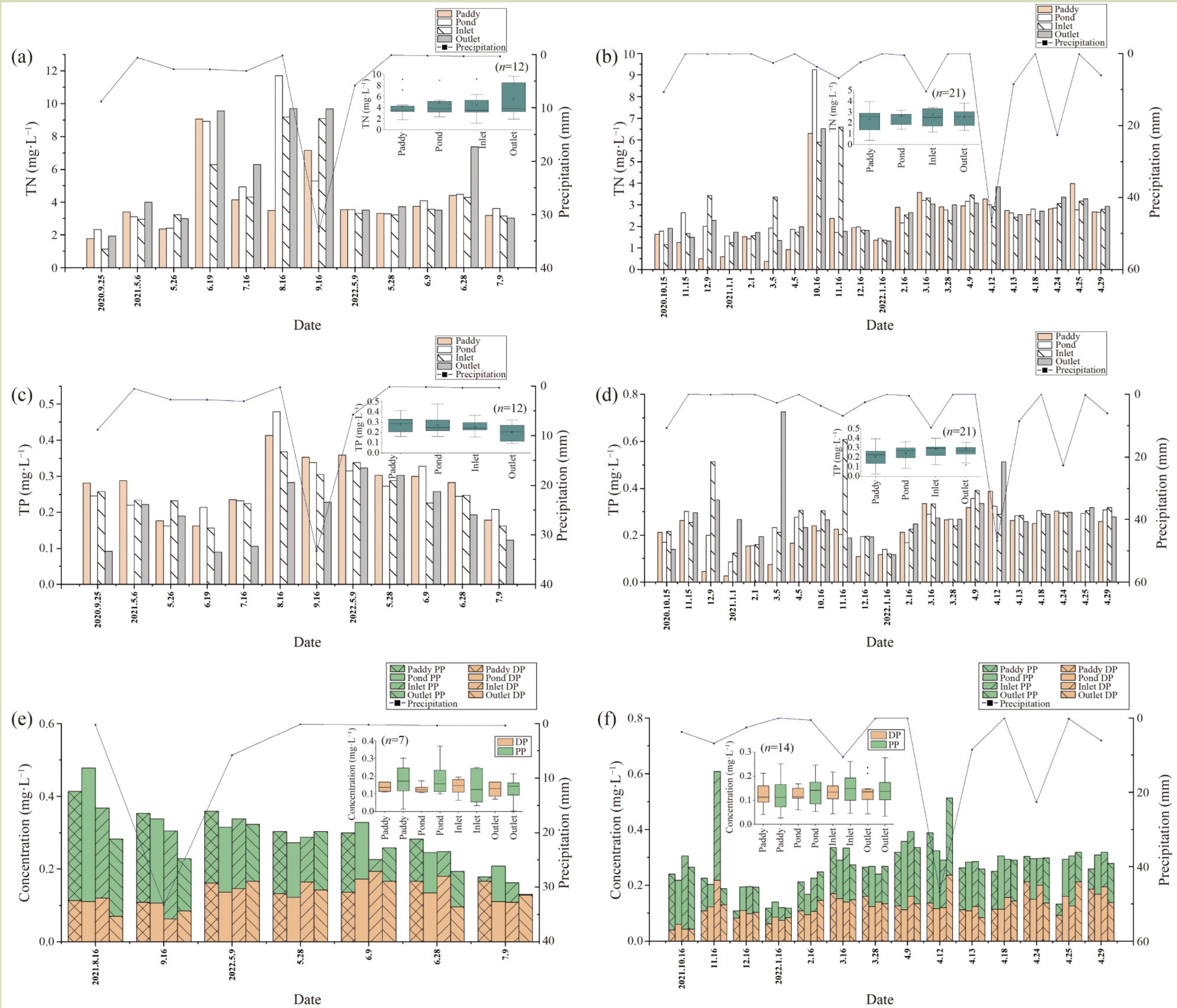


Fig. 8 Changes in nutrient concentration in the paddy-ditch-pond sampling site: total nitrogen (TN) in the rainy (a) and dry (b) seasons, total phosphorus (TP) in the rainy (c) and dry (d) seasons, and combined dissolved and particulate phosphorus (DP and PP) in the rainy (e) and dry (f) seasons.

resulting in poor water quality at the ditch. In the dry season, TN concentrations in paddy, ponds and ditches changed little overall, but changed greatly in individual periods. Most of the abrupt change could be attributed to crop planting and fertilizer application activities. In the second half of each year, local farmers planted lettuce, mustard, rapeseed and other crops on sloping fields, specifically lettuce in early October, rapeseed in mid-October and beans in early November. In Fig. 8(b), TN concentration at the inlet of the ditches and ponds was higher in October and November due to fertilizer application, but the TN concentration decreased to some degree at the ditch outlet.

In the rainy season, the outlet TP concentration was generally lower than the inlet, indicating that ponds and ditches contribute to intercepting phosphorus. In the dry season, nearly half of the outflow TP was greater than the pond TP, which may be caused by more frequent agricultural activities. Compared with the surface water environmental standards in China, the P concentration in rainy season and dry season was mostly lower than the surface water class V standard of 0.4 mg·L^{-1}. As evident in Fig. 8(e, f), 42.9% of the P in runoff was DP during the rainy season. In the rainy season samples of 2022, the PP at the ditch outlet had a decreasing trend whereas DP had an increasing trend. This may be due to the fact that most of the rainy season samples of 2022 were collected on sunny days or light rain, with less rainfall and better deposition environment for PP. Overall, DP in paddies, ponds and ditches accounted for 50% of the TP in the dry season. At the ditch outlet, both DP and PP decreased. It was concluded that the combination of ditch-pond can intercept PP to some degree.

S3: Long ditch

The change in nutrient concentrations in long ditch is shown in Fig. 9. TN concentrations in the rainy season were generally higher than that in the dry season. Overall, the TN concentration at the ditch outlet was higher than that at the inlet during the rainy season. There were two reasons for the phenomenon. One reason was that rainfall was heavy, and the overflow of the pond next to the ditch caused the outflow TN concentration to rise. Another reason was that rainfall washed away sediment from the bottom of the ditch and released pollutants into the flowing water, making the concentration at the outlet greater than that at the inlet. Taking into consideration different periods during the rainy season, the variation range of TN concentrations in ditches was large, especially in May and June, and the TN concentration was lower the rest time. This was due to the application of fertilizer to rice and maize from April to June. Since there was no water baffle between the paddy and the ditch, after the application of mineral fertilizer, some nutrients could be lost to the ditch during rainfall, which would increase the TN concentration at the ditch outlet. In the dry season, the TN concentration of the ditches mostly met the surface water class V standard of 2 mg·L^{-1}. The period of TN concentration exceeding the standard mostly occurred in the period of frequent agricultural

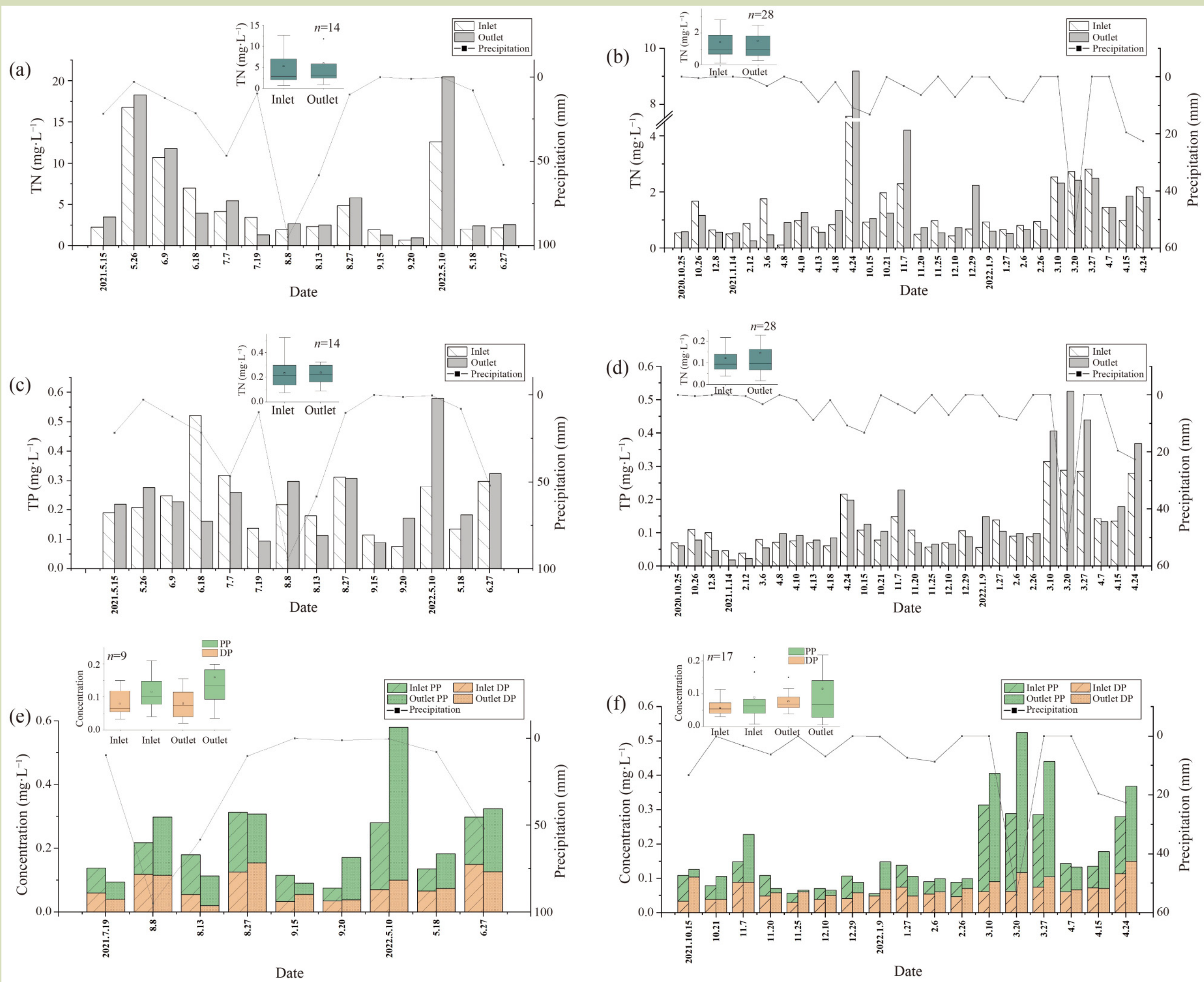


Fig. 9 Changes in nutrient concentrations in the long ditch site: total nitrogen (TN) in the rainy (a) and dry (b) seasons, total phosphorus (TP) in the rainy (c) and dry (d) seasons, and combined dissolved and particulate phosphorus (DP and PP) in the rainy (e) and dry (f) seasons.

activities in the catchment, which was consistent with the period of fertilizer application to rice and maize.

Overall, TP concentration mostly met the surface water class V standard of 0.4 mg·L^{-1}. In terms of seasons, TP concentration in the rainy season was generally higher than that in the dry season. In the rainy season, the fluctuation TP concentration in ditch runoff was large, and was between 0.075 and 0.58 mg·L^{-1}. When there was heavy rainfall, the TP concentration at the ditch outlet did not increase sharply, because paddy drainage and surface runoff were large, which led to dilution pollutants. In general, in the rainy season, the rapid drainage effect of ditches was greater than their pollutant retention capacity. In the dry season, TP concentration was between 0.055 and 0.525 mg·L^{-1}. Most TP concentration met the surface water class III standard of 0.2 mg·L^{-1}. In March and April, when fertilizer application was more frequent, the TP concentration at the ditch outlet was significantly higher than that at the inlet. From November to February, when there was less precipitation, the TP concentration at the ditch outlet was lower than or similar to the TP concentration at the inlet. As evident in Fig. 9(e, f), 52.9% of P in runoff was PP during the rainy season, and the overall P concentration at the outlet was higher than that at the inlet. In dry season runoff, 77.8% of P was PP. Overall, the average proportion of PP/TP ratio at the ditch outlet was higher than that at the inlet, indicating that PP was the main form of phosphorus loss in the catchment. In March and April, when fertilizer application was frequent, the phosphorus concentration in the ditch increased sharply. After topdressing in May, the phosphorus concentration in ditches decreased. It was evident that in the early stage of rice growth, the outflow of surface water from paddies can create pressure on the surrounding water environment.

S4: Ditch-pond (soil and concrete ditches) combination

The variation of pollutant concentration in the ditch-pond combination is shown in Figs. 10–12. As evident in Fig. 10, during the dry season, the TN concentration in soil ditches was between 0.674 and 6.83 mg·L^{-1}, and in concrete ditches between 0.428 and 5.79 mg·L^{-1}. The average concentrations at the inlet of soil and concrete ditches were 3.73 and 2.29 mg·L^{-1}, and 2.54 and 2.46 mg·L^{-1} at the outlet, respectively.

Comparison of Fig. 10(b, d) reveals that the TN concentration at the inlet of soil ditch was much higher than that at the inlet of concrete ditch. There were two reasons possible for this phenomenon. One reason may be that December, March and April when fertilizer was applied to mustard, rice and maize respectively, and a large amount of mineral fertilizer, mainly nitrogen fertilizer, would have been applied. In the event of rainfall, some nutrients flowed into the water body in runoff. Another reason could be that when water flowed from the pond into the soil ditch, it scoured the soil on the wall of the ditch, resulting in the loss of nitrogen from the soil to the water body. However, due to the nature of the concrete ditch, the TN concentration at the inlet of concrete ditch did not increase significantly. Overall, in the dry season, the TN interception capacity of the soil ditch was greater than that of the concrete ditch, which may be because the sediment in the soil ditch, and soil and vegetation on both sides, can absorb and intercept more pollutants.

In the rainy season, the TN concentration in the soil ditch was between 2.64 and 14.9 mg·L^{-1}, and between 2.01 and 10.4 mg·L^{-1} in the concrete ditch. The average concentration at the inlet of soil and concrete ditches were 6.73 and 5.57 mg·L^{-1}, respectively, and the average concentration at outlet were 6.03 and 5.29 mg·L^{-1}, respectively. Overall, the TN concentration in the soil ditch was higher than it of concrete ditch, which may be due to the increase of water nitrogen concentration caused by more precipitation in rainy season and soil eroded by rainfall. Overall, the nitrogen interception capacity of concrete ditches was higher than that of soil ditches in rainy season.

In dry season, the TP concentration in soil ditch was between 0.115 and 0.450 mg·L^{-1}, and between 0.073 and 0.515 mg·L^{-1} in the concrete ditch. The average concentration at the inlet of soil and concrete ditches were 0.25 and 0.26 mg·L^{-1}, respectively, and the average concentration at the outlet were 0.22 and 0.24 mg·L^{-1}, respectively. The reason why the TP concentration at the soil ditch inlet did not fluctuate as much as it did or of TN could be that the use of nitrogen fertilizer was much higher than for phosphate fertilizer.

In the rainy season, the TP concentration in soil ditch was between 0.094 and 0.635 mg·L^{-1}, and between 0.130 and 0.573 mg·L^{-1} in the concrete ditch. The average concentration at the inlet of soil and concrete ditches were 0.33 and 0.27 mg·L^{-1}, respectively, and the average concentration at outlet was 0.26 and 0.29 mg·L^{-1}, respectively. Overall, the phosphorus interception in the soil ditch on was higher than in the concrete ditch. The TP concentration at the ditch outlet was generally lower than that of the pond, indicating that the water body had been purified to some degree while flowing through the ditch.

From the Fig. 12(b, d), it can be concluded that in the dry season the PP concentration at the soil ditch outlet was lower than in the pond, and the DP concentration at the ditch outlet was slightly higher than in the pond DP. The PP/TP ratio in the

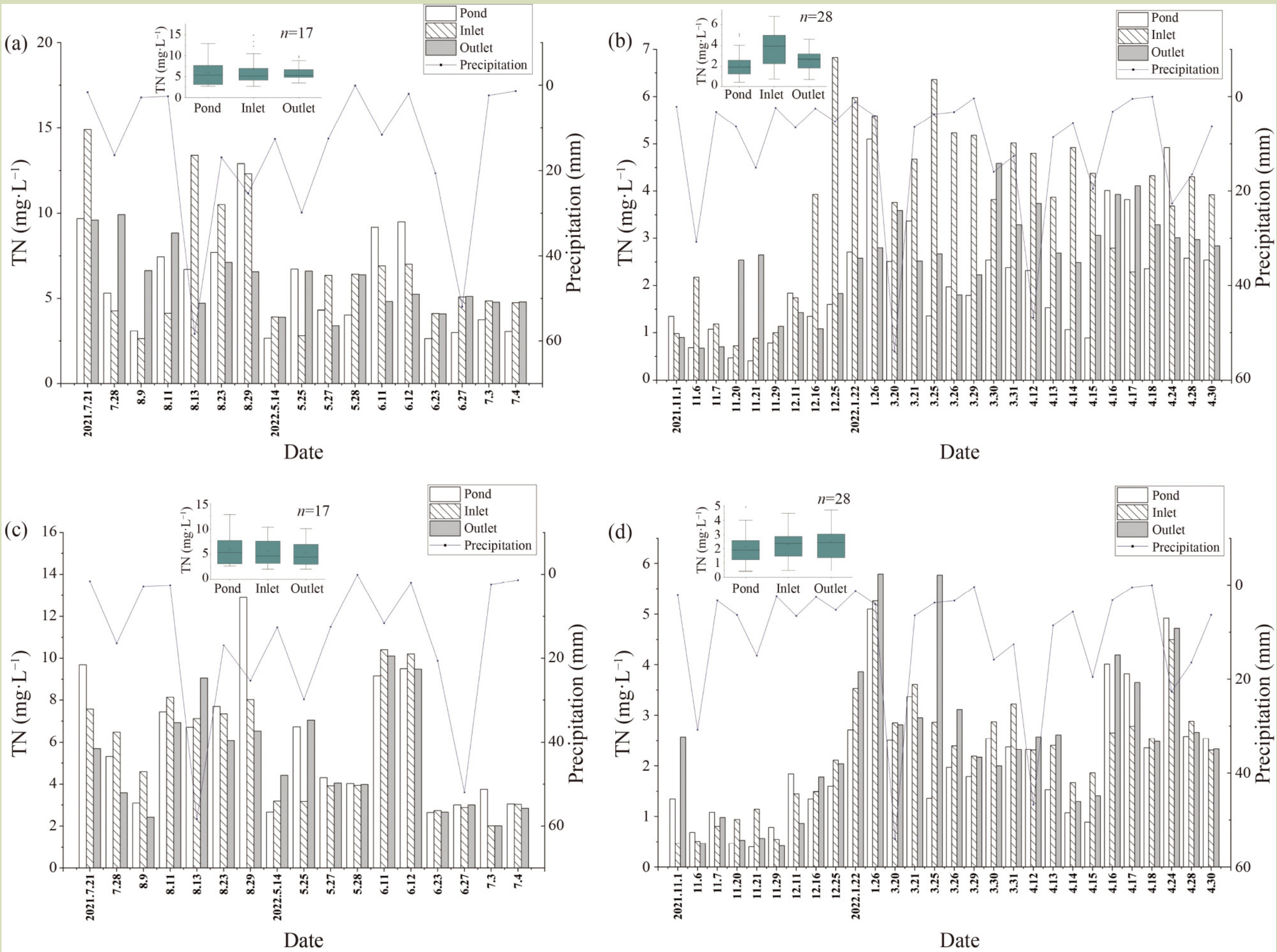


Fig. 10 Changes in total nitrogen (TN) concentrations in the ditch-pond (soil and concrete ditches) combination site: soil ditches in the rainy (a) and dry (b) seasons, and concrete ditches in the rainy (c) and dry (d) seasons.

inlet of soil and concrete ditches were 0% to 76.9% and 27.4% to 77.4%, with averages of 47.4% and 57.9%, respectively. The PP/TP ratio in the outlet of soil and concrete ditches were between 20.4% and 19.0%, with averages of 46.9% and 53.2%, respectively. Considering these averages, it can be seen that after the pond water passes through the ditch, the overall PP decreased, and PP interception of the concrete ditch was higher than in the soil ditch.

In the rainy season, the PP/TP ratio in the soil and concretion ditch inlets were between 0% to 79.3%, and 32.3% to 76.0%, with an average of 53.5% and 58.0%, respectively. The PP/TP ratio in the outlet of soil and concrete ditches were between 0% and 74.8%, and 45.3% to 80.5%, respectively, with averages of 52.4% and 62.6%, respectively. In generally, the fluctuation range of DP concentration in ponds and ditches was less than that for PP. The large fluctuation range of PP concentration was mainly affected by rainfall.

4 DISCUSSION

Large water bodies, especially lakes and wetlands, have been given more attention as important geographical features of global terrestrial systems[26]. Compared with large water bodies, small water bodies such as ponds are common, but receive limited attention. Small water bodies are often ignored in the national resource survey because of their small area[27]. For example, ponds are often overlooked freshwater ecosystems due to their relatively small area to the total water surface of the earth[28,29]. The spatial distribution of ponds is related to the local annual precipitation[13]. Downing et al.[30] showed that there was a positive correlation between the surface area ratio of ponds and the average annual precipitation. The increase in the number of small ponds is mainly due to the fact that they are used in long-established farming practice as irrigation facilities, so a large number of ponds have been built to meet the irrigation needs of some

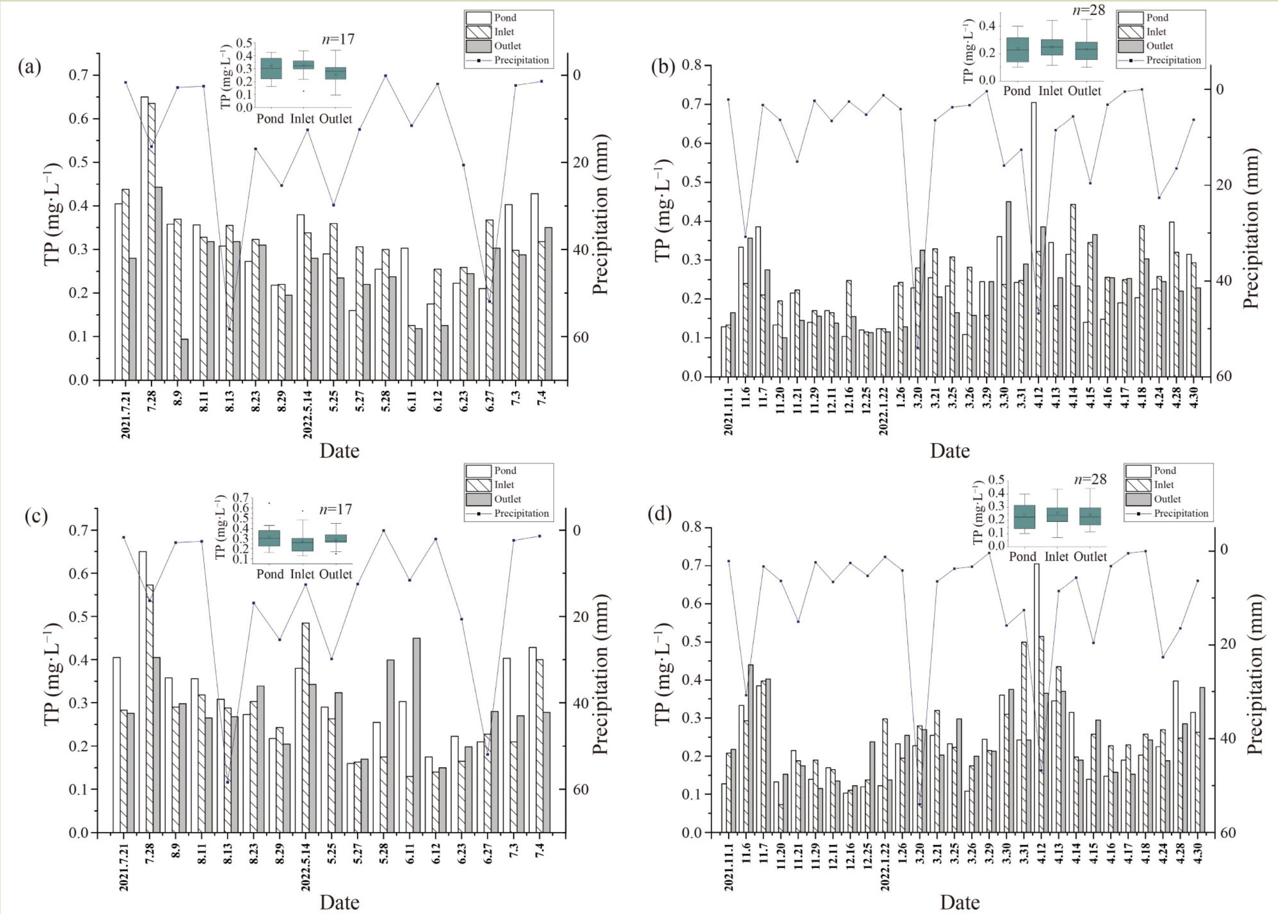


Fig. 11 Changes in total phosphorus (TP) concentrations in the ditch-pond (soil and concrete ditches) combination site: soil ditches in the rainy (a) and dry (b) seasons, and concrete ditches in the rainy (c) and dry (d) seasons.

agroecosystems. In addition, farming practice has diversified in recent years with the conversion of established paddies to ponds for fish culture. Ponds have an important influence on the drainage capability of a catchment. Lv et al.[13] showed that ponds had doubled in China and the drainage area associated with ponds had increased from 13.2% to 35.4% of the total catchment area. This highlights the landscape impact of ponds, and their effect on ecological processes within catchments cannot be ignored. Ditches and ponds are considered to have strengthen pollution interception and hydrological regulation. In the case of extreme rainfall, the water storage function of the pond is important for regulating hydrology in a catchment. Some studies have shown that the construction of ditches has a significant impact on the confluence path, draining area and confluence time with a catchment. Sun et al.[31] report that ditches and ponds not only significantly increased drainage density in a catchment, but also increased the confluence time, which is more conducive to the interception of pollutants.

In addition to the standard irrigation and aquaculture functions, our study found that the ditches and ponds make a key contribution to nutrient reserve and pollutant removal. This is consistent with the study of Cai et al.[32]. In our study, both ditches on their own or in combination with ponds can intercept of some nitrogen and phosphorus lost from fields and paddies in runoff. Over the observation period, the average TN and TP concentrations in the catchment in the rainy season were 1.94 and 0.26 mg·L^{-1}, respectively. In the dry season, the average TN and TP concentrations in the catchment were 1.23 and 0.23 mg·L^{-1}, respectively. In the ditches and ponds, the average TN and TP concentrations exported during the rainy season were 5.66 and 0.275 mg·L^{-1}, and 2.50 and 0.255 mg·L^{-1} in the dry season, respectively. Compared with these data, the TN and TP concentrations in the outlet of ditches and ponds were higher than in the whole catchment. When the runoff from the ditch and pond flows into the main stream via different paths, the pollutants are somewhat diluted. In the dry season, the TN and TP concentrations in ditches and ponds

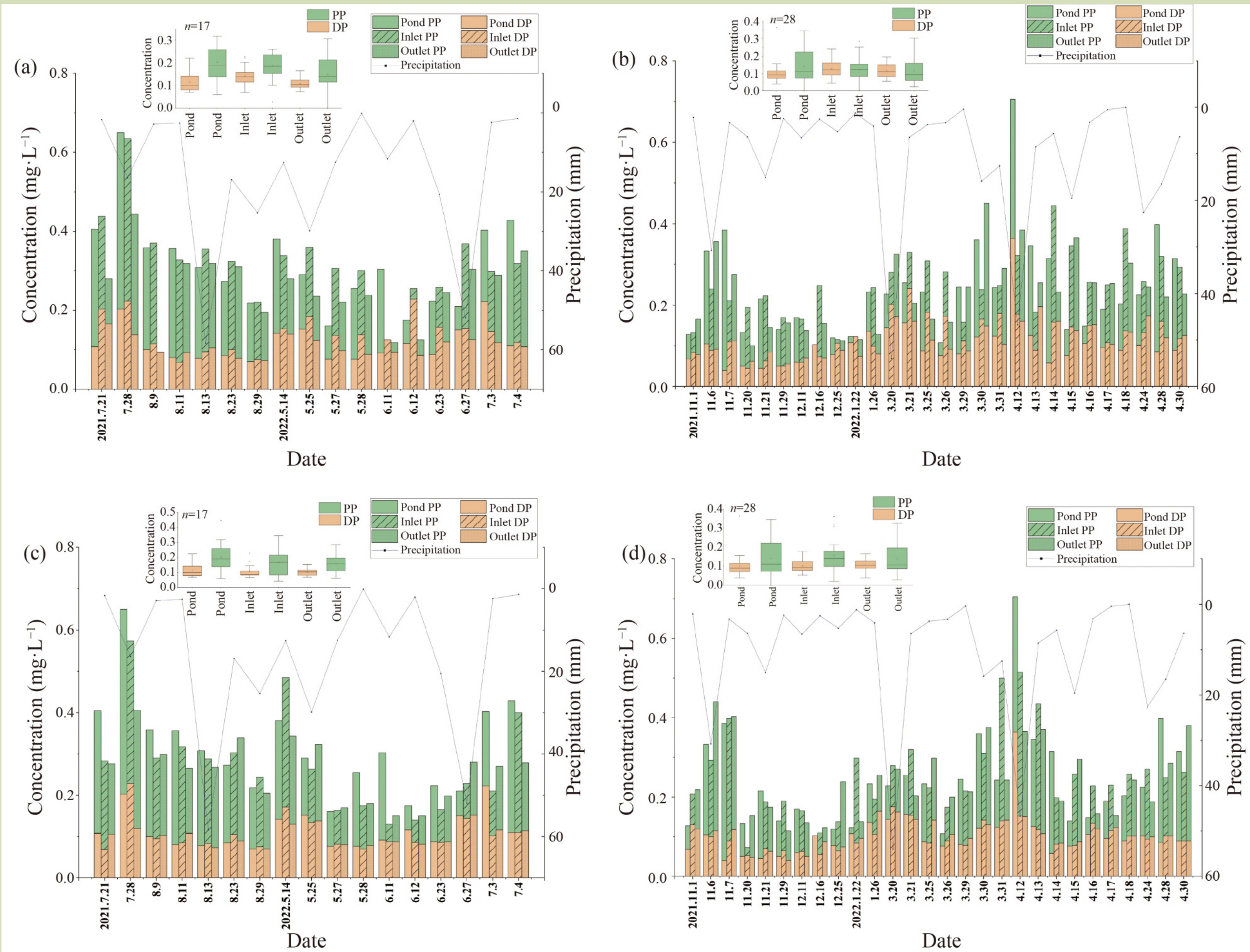


Fig. 12 Changes in combined dissolved and particulate phosphorus (DP and PP) concentrations in the ditch-pond (soil and concrete ditches) combination site: soil ditches in the rainy (a) and dry (b) seasons, and concrete ditches in the rainy (c) and dry (d) seasons.

was lower than that in the rainy season, which was reflected in the whole catchment. Therefore, the change of the concentration of pollutants in ditches and ponds also affects the change of the pollutants in the catchment to some degree.

In this study, the loss of nitrogen in farmland was greater than for phosphorus. The TN lost during the period of fertilizer application in 2020 and 2021 was 25.4% and 16.5% of the annual TN, respectively. Similarly, and the TP lost during the period was 25.9% and 16.4% of the annual TP, respectively. This is indicative of the TN in runoff mainly coming from soil. To some degree, this also explains the sharp increase of water pollutants in the catchment during rainfall. As Jinglinxi catchment is a representative agricultural catchment, long-term fertilizer application leads to the accumulation of nutrients, including nitrogen and phosphorus, in the soil. Due to the often excessive application and accumulation of nitrogen and phosphorus in soil, the agricultural non-point source pollution caused by these during rainfall erosion in non-fertilizing period cannot be ignored. By sampling and analyzing the soil in the study area, the surplus accumulation and loss potential of nutrients in the soil can be taken into account in subsequent modeling. By studying the loss of pollutants in paddy runoff, some studies showed that 69.8% of the phosphorus loss comes from soil, and only a small part comes from fertilizer[24]. This shows the importance of undertaking soil testing and informed fertilizer application in rural areas. Concurrently, it will also be necessary to increase farm knowledge of the scientific principles of application of mineral fertilizers in rural and urban areas.

Ditches, ponds and cropping fields constitute an integrated agricultural system[33]. Nutrient interception in ditches and ponds can reduce the quantum and concentration of pollutants and thereby protect the downstream water quality[34]. In our study, the changes in pollutants in ditches and ponds were not always positive. The negative changes were mainly due to the following reasons: (1) heavy rainfall washed nutrients from the sediments in the ditches and ponds into the flowing water, so that the concentration of pollutants at the outlet was higher than that at the inlet; (2) fertilizer application before rainfall led to loss of nutrients through runoff; (3) continuous rainfall shortened the hydraulic retention time of runoff in ditches and ponds decreasing pollutant sedimentation and conversion; and (4) topography of the upland area with its purple soil particularly subject to water erosion in such areas[35]. In comparison, lowland areas have gentler slope, and fluctuations in water quality are smaller and the change rate of nutrient flows is more susceptible to the influence of hydraulic retention time and paddy drainage[18]. Shen et al.[1] noted that when considering single rainfall events, the nutrient flow change rate in ditches and ponds is more likely to be negative. In addition, by comparing rainy and dry seasons, our study showed that the effect of ditches on intercepting pollutants in dry season is greater than in the rainy season. In the study area, being in an upland catchment subject to extreme rainfall, the rapid discharge function of ditches and the water storage function of ponds are particularly important. In the case of low rainfall in dry season, the TP concentration at ditches outlets was mostly lower than for ponds outlets, but the reverse was observed in the rainy season. For TN, there was no obvious change between seasons. In the case of heavy rainfall, rainfall erosion of the sediment in the ditch and lateral seepage into the ditch may lead to the concentration of pollutants at the ditch outlets being higher than at pond outlets. Given phosphorus can be easily transported with sediments, its concentrations vary significantly between the rainy season and the dry season. Sometimes ditches and ponds can be a source of pollutants, but heavy rainfall can cause more runoff and somewhat dilutes the concentration of pollutants.

To sum up, in the dry season, ditches and ponds are more likely to act as sinks, which can intercept and reduce non-point source pollutants. While during the rainy season, ditches and ponds become sources of pollutants as more pollutants are released from sediments into the flowing water with the higher flow rates from heavy rainfall. Although ditches and ponds sometimes become sources of pollutants, they contribute to the regulation of the hydrology and water quality within a catchment. In our study, by comparing soil and concrete ditches, it is found that the concrete ditches performed better, with sediment settling in the dry season and being removed in the rainy season. Shen et al.[36] discussed nitrogen deposition in upland areas and the importance of paddy management to reduce pollutants at field scale. It is also becoming increasingly important to treat the pollutants with catchments using farmland-ditch–pond system. Studies have also shown that by controlling the drainage function of the paddy-ditch-pond, 6% to 10% of irrigation water can be saved, and the nitrogen runoff directly into the waterbodies can be reduced by 82% to 100%[37]. Through these measures, ditches and ponds can be effectively transformed from sources to sinks in the rainy season. Therefore, balancing the function of drainage and pollutant interception in ditch and pond systems can maximize their ecological role in a catchment.

5 CONCLUSIONS

In this study, the ecological function of ditches and ponds in a representative upland catchment was analyzed. It was found that the number of small ponds (< 500 m^2) in 2019 and had increased by 75% since 2009, and the length of ditches had increased by 31.8%. The results also showed that in the dry season, ditches and ponds can serve as important sinks of agricultural pollutants. However, ditches and ponds can be sources of pollutants during the rainy season. With sedimentation in ditches in the dry season followed by sediment mobilization in the rainy season, ditches and ponds can change from sinks to sources. Thus, we conclude that the ditch-pond system can be effectively used as an ecological engineering tool for regulating hydrology and water quality in upland agricultural catchments.

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Compliance with ethics guidelines

Yiwen Wang, Lei Chen, Kaihang Zhu, Chenxi Guo, Yu Pu, and Zhenyao Shen declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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