Chapter 7

Water Quality in Irrigated Paddy Systems

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Abstract

Irrigated paddy rice (*Oryza sativa* L.) is a staple food for roughly half of the world's population. Concerns over water quality have arisen in recent decades, particularly in China, which is the largest rice-producing country in the world and has the most intensive use of nutrients and water in rice production. On the one hand, the poor water quality has constrained the use of water for irrigation to paddy systems in many areas of the world. On the other hand, nutrient losses from paddy production systems contribute to contamination and eutrophication of freshwater bodies. Here, we review rice production, water requirement, water quality issues, and management options to minimize nutrient losses from paddy systems. We conclude that management of nutrient source, rate, timing, and placement should be combined with the management of irrigation and drainage water to reduce nitrogen and phosphorus losses from paddies. More research is needed to identify cost-effective monitoring approaches and mitigation options, and relevant extension and policy should be enforced to achieve water quality goals. The review is preliminarily based on China's scenario, but it would also provide valuable information for other rice-producing countries.

Keywords: water quality, paddy, irrigation, water management, nutrient management

1. Introduction

Rice (*Oryza sativa* L.) is a staple food for roughly 50% of the world's population. Globally, rice is planted on a total of 155 million hectares of land, and annual rice production amounts to up to 480 million metric tons [1]. Nearly 90% of the rice is produced in Asian countries. The top seven rice-producing countries, i.e., China (30%), India (22%), Indonesia (8%), Bangladesh (7%),

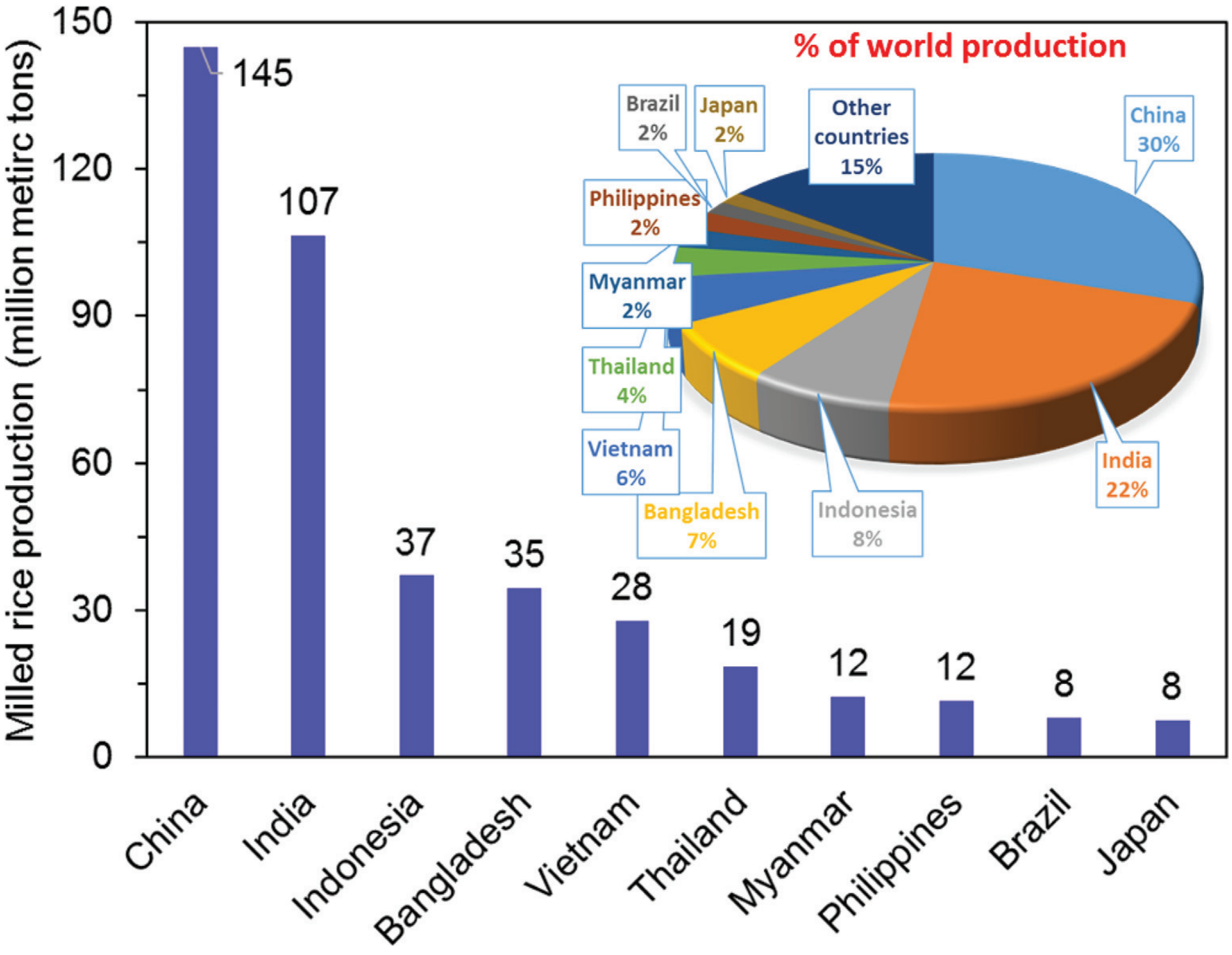

Figure 1. Rice production of world top 10 countries in 2016 (based on data from www.statista.com; [2]).

Vietnam (6%), Thailand (4%), and Myanmar (3%), collectively account for 80% of the world's total rice production (**Figure 1**).

Worldwide, agriculture accounts for 70% of all water consumption, far more than the 20% for industry and the 10% for domestic use (http://www.worldometers.info/water/). As water is needed throughout the rice-growing season, paddy fields altogether consume up to 90% of the total water used for irrigation in Asia [3]. Therefore, paddy water management is crucial to save water resources in the context of water quantity. Meanwhile, there have been frequent reports on environmental and ecological concerns related to paddy production. In particular, water quality issues have received increasing attention. Rice is commonly grown in regions close to inland streams and lakes, which is a double-bladed sword. On the one hand, such a landscape arrangement resulting from long-term human adaptation to the environment allows the most convenient and economic use of water resources in agricultural production. On the other hand, it generates risks of eutrophication in the streams and lakes where the ecological systems are sensitive to nutrients. Indeed, several previous studies identified phosphorus losses from paddy production systems as an important cause of eutrophication in the local, enclosed lakes in China (e.g., [4, 5]). This is because such regions are commonly characterized by enhanced, extensive hydrological networks between paddy fields and between the fields and their adjacent water bodies, which elevate the risk of nutrient runoff from paddy fields to the waters. In the context of water quality, both nutrient and water management are of great importance.

In this chapter, we reviewed water quality issues related to paddy rice production and discussed the potential strategies to reduce nutrient losses to the water environment. As China is the largest rice-producing country in the world, we focused the review and discussion on China's scenario. Even so, we included information from other countries whenever it was relevant.

2. Rice production in China

In China, rice is the first major food crop, owning a total planting area of 30 million hectares. The rice production of 207 million metric tons is equivalent to 34% of the total grain crop production [6]. Rice production is mainly concentrated in three geophysical regions: Yangtze River Basin (covering provinces of Hunan, Jiangxi, Jiangsu, Hubei, Sichuan, Anhui, Yunnan, Zhejiang, Chongqing, Guizhou, and Shanghai), Southeast Coastal Plains (Guangxi, Guangdong, Fujian, Hainan, Hong Kong, Macao, and Taiwan), and Northeast Plains (Heilongjiang, Jilin, and Liaoning; **Figure 2**). Specifically, the Yangtze River Basin accounts for 65% of China's total rice planting

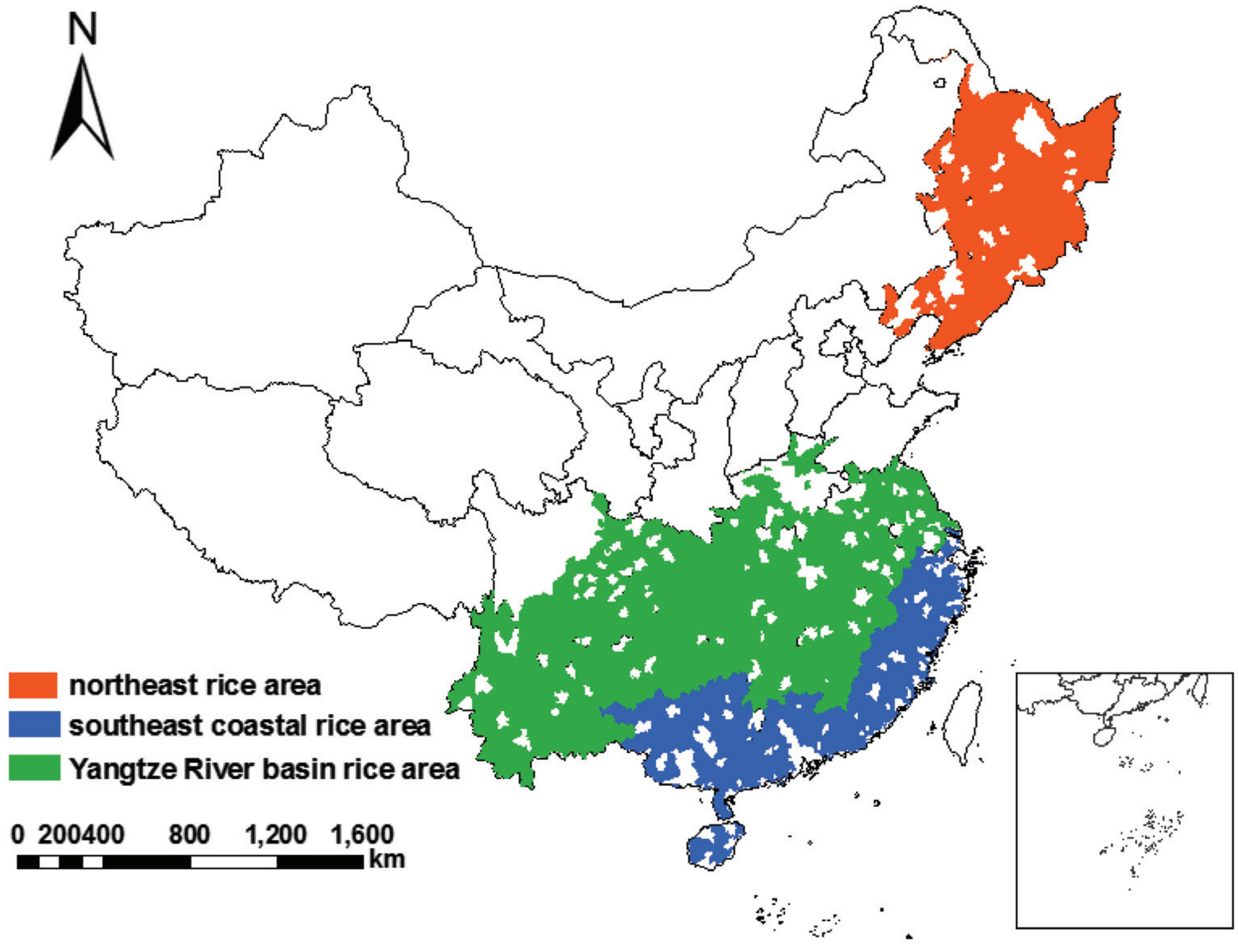

Figure 2. Major rice-producing regions in China [7].

area, followed by the Southeast Coastal Plains (16%), the Northeast Plains (15%), and other regions (4%; **Figure 3**). Due to its nature of requiring large amounts of water throughout the growing season, over 80% of the rice planting areas are located in Southern China where annual precipitation ranges from 1000 to >2000 mm. Notably, the rice planting areas make up over 10% of the total provincial areas in Hunan, Jiangxi, Jiangsu, Hubei, Anhui, Shanghai, and Guangdong. In line with the patterns of planting areas, the Yangtze River Basin dominates the national rice production (65%), which is followed by the Northeast Plains (16%), the Southeast Coastal Plains (14%), and other regions (5%; **Figure 3**). In 2016, the top five rice-producing provinces, i.e., Hunan,

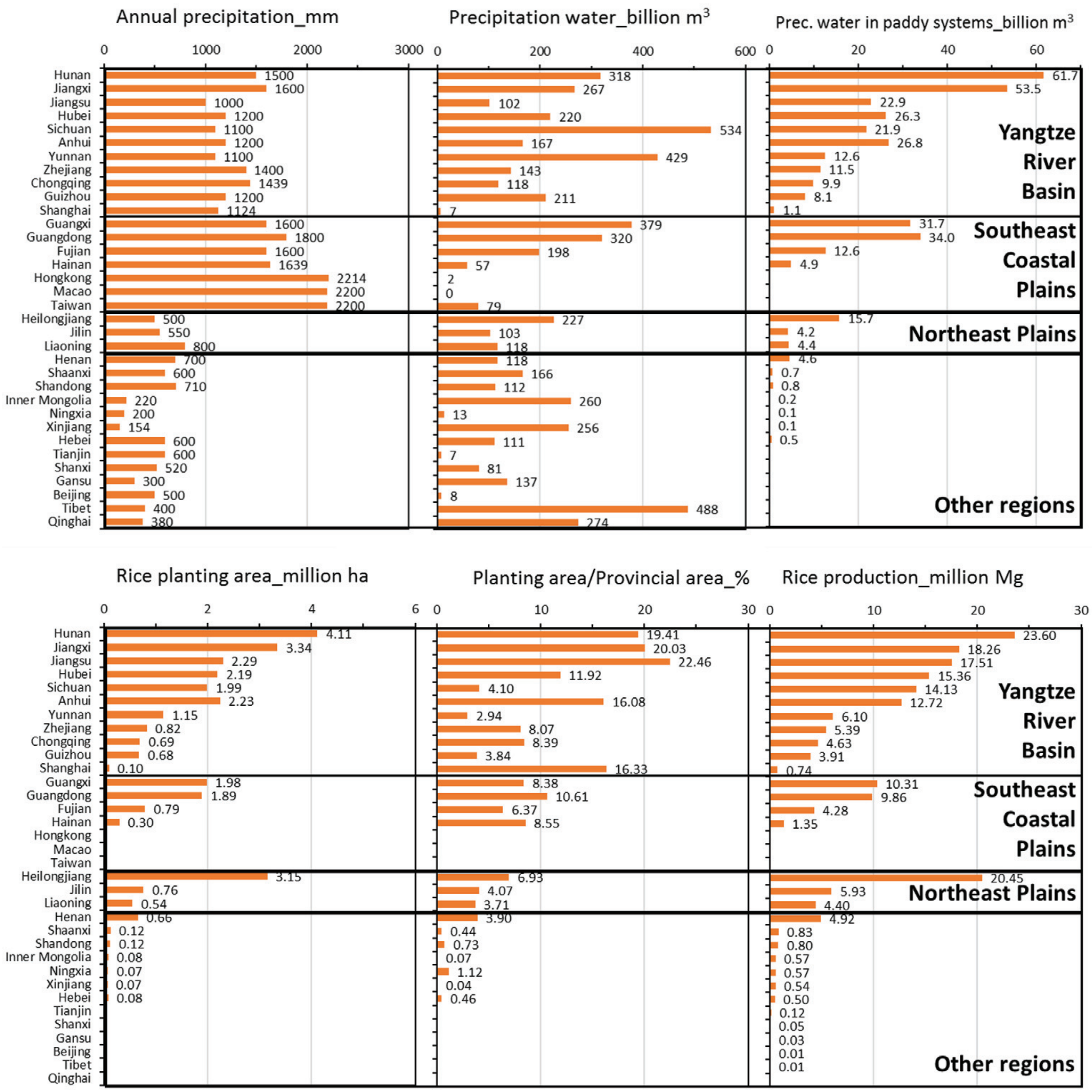

Figure 3. Annual precipitation, precipitation water volume, rice planting area, and rice production by provinces of China in 2016 [8, 9].

Heilongjiang, Jiangxi, Jiangsu, and Hubei, produced 51% of China's total rice. In combination, these five provinces receive a total of 180 billion m^3 of precipitated water in paddy fields, which is 49% of the precipitated water received by all paddy fields.

Across the world, rice cropping systems vary from monoculture (e.g., northern China) to double (e.g., southern China) and triple cropping (e.g., India and Bangladesh) depending on climatic conditions. In most areas of China, the rice-growing season starts in spring with steeping paddy fields and the transplantation of rice seedlings and ends in the fall with the draining of the fields and harvesting rice grains. Despite large variabilities in paddy management by regional and local conventions as well as available technologies, rice cultivation is commonly characterized by the flooding of the paddy fields during most of the growing season along with intensive irrigation and fertilization. Flooding the rice fields is essential for most rice varieties to maintain good growth and achieve high yields. **Figure 4** presents typical management schedules for paddy rice in Hubei Province, Yangtze River Basin, China. Due to favorable climatic conditions, the vast area of this province allows a double-cropping system represented as the rotation of rice with winter wheat (*Triticum aestivum* L.) or oilseed rape (*Brassica napus* L.). The rice-growing season starts in late May with irrigation to steep field for a few days, followed by plowing and basal fertilization prior to transplanting rice seedlings. During the process of transplanting rice in early June and harvesting of rice in late September, there are often a couple of fertilizer top dressings to meet rice's need of nitrogen. There are also a number of irrigation and drainage operations to maintain appropriate depths of ponding water.

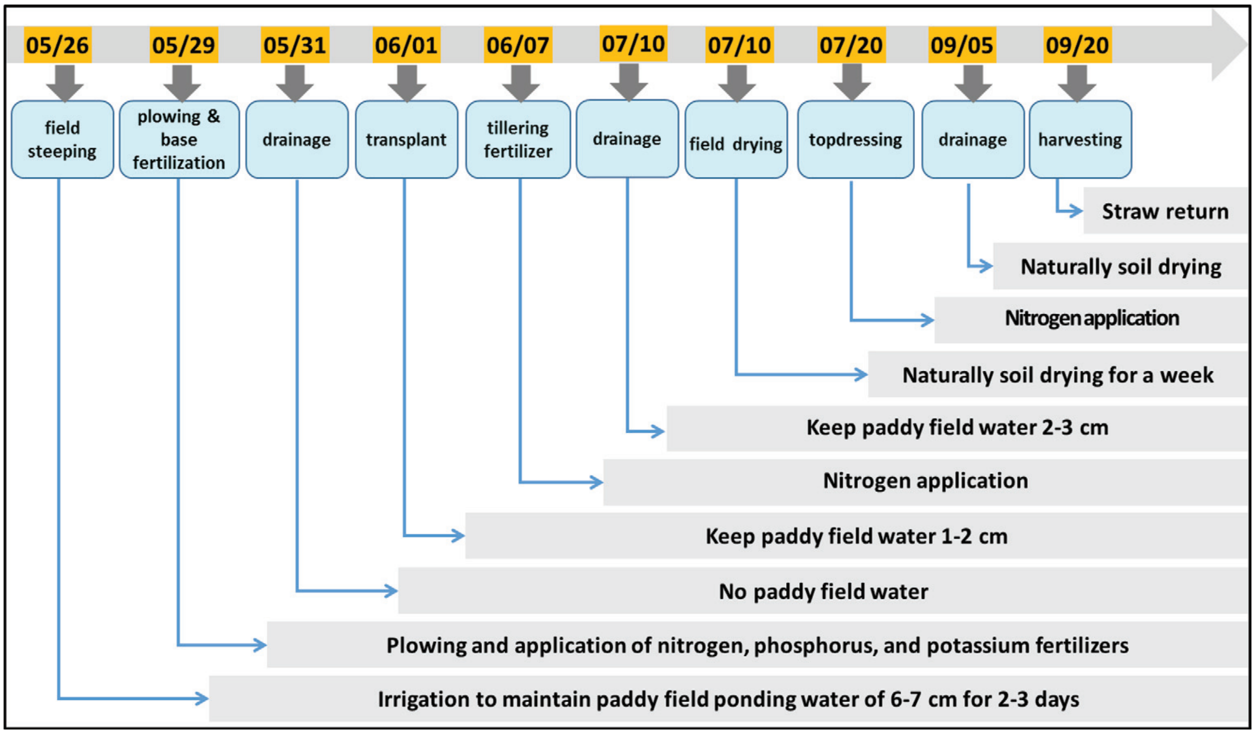

Figure 4. Typical management schedules for paddy rice in Hubei Province, Yangtze River basin, China.

3. Water requirement of rice

Water requirement of rice crop is influenced significantly by environmental conditions such as climate. For example, in Bangladesh, with a tropical climate all over the country, more than 2000 liters of water is required to produce every kilogram of rice dry substance. In China, where rice production areas span from the cold Northeast to the subtropic and tropic South, such water requirement ranges from 400 to 1500 liters. Based on a 30-year meteorological data, statistics of crop growth stages, crop water requirement, and net irrigation requirement, Liu et al. [10] estimated the requirement of water and irrigation for the rice across China, using the FAO Penman-Monteith equation and crop coefficient method. Across the three major rice-producing regions, the rice crop requires 250–950 mm of water, which is greater than the 200–620 mm required for corn (*Zea mays* L.), wheat, or cotton (*Gossypium* spp.) crops. Likewise, rice requirement for irrigation (usually 70–500 mm) is also greater than the other crops (0–350 mm).

Region	Province	Crop	Water requirement (mm)	Net irrigation requirement (mm)
Yangtze River Basin (middle and lower portion)	Hunan, Jiangxi, Jiangsu, Hubei, Anhui, Zhejiang, Shanghai	Early rice	400–580	80–300
		Middle rice	500–800	150–420
		Late rice	500–650	150–400
		Spring corn	250–550	0–200
		Summer corn	330–450	100–200
		Cotton	450–620	50–300
Yangtze River Basin (upper portion)	Yunnan, Guizhou, Sichuan, Chongqing	Early rice	350–700	100–500
		Middle rice	550–950	100–500
		Late rice	400–700	100–350
		Spring corn	300–500	10–250
		Summer corn	300–450	20–100
		Winter wheat	200–600	100–350
Southern Coastal Plains	Guangxi, Guangdong, Fujian, Hainan	Early rice	400–580	70–300
		Middle rice	450–570	90–250
		Late rice	600–700	100–450
		Spring corn	200–400	0–120
		Summer corn	250–420	50–150
		Cotton	450–520	30–180
Northeast Plains	Heilongjiang, Jilin, Liaoning	Middle rice	250–750	80–450
		Spring corn	200–500	10–220
		Spring wheat	250–450	100–300

Table 1. Water requirement and irrigation requirement of the rice crop in comparison to other crops in China (adapted from [10]).

It should be noted that rice water requirement and net irrigation requirement vary widely both between regions and within regions (**Table 1**), reflecting the spatial and temporal variability of water needs by the crop. Furthermore, water requirement and irrigation requirement also differ with rice varieties and growing seasons. Typically, middle rice and late rice need more irrigation water than early rice, due to their prolonged growing seasons.

4. Water quality issues in paddy systems

Water quality problems evolve at both sides of the paddy systems, i.e., inputs of contaminants with irrigation water and exports of nutrients to the surrounding water environment. In the case of contaminant inputs with irrigation water, wastewater or reclaimed wastewater irrigation has generated particular concerns [11–14]. In a recent review on the impacts of wastewater irrigation, Amin et al. [11] concluded that even though wastewater is a valuable source of nutrients, it may contribute many emerging contaminants to the water environment. Indeed, wastewater may contain an array of contaminants such as heavy metals, pathogens, and organic contaminants, along with nutrients (e.g., those listed in **Table 2**). As a result, there is a potential risk of contamination of both shallow groundwater and surface water associated with wastewater irrigation [14]. In a field study, Cao and Hu [12] found that irrigation with copper-rich wastewater increased soil copper concentration in the surface soil layer (0–10 cm) by sixfold and reduced rice yield by 18–25% as compared with the control with normal irrigation water. Accumulation of copper in the surface soil greatly elevated the potential risks of copper pollution through surface runoff. Elsewhere, however, Kang et al. [13] found no adverse effects of reclaimed wastewater on both rice grains and the paddy fields after appropriate treatments of the wastewater. These results point to the importance of monitoring and treatment of wastewater before use for irrigation.

In the case of nutrient exports to the surrounding water environment, the issue of water quality is closely related to water and nutrient turnover and management in the paddy systems. Budget of water in paddy systems involves water inputs in the forms of rainfall and irrigation and water outputs through evapotranspiration, runoff, and deep percolation (**Figure 5**). Rainfall is a

Nutrients	Unit	Range	Contaminants	Unit	Range
Total nitrogen	mg/L	20–70	Total solid	mg/L	390–1230
Total phosphorus	mg/L	4–12	Total dissolved solid	mg/L	270–860
Total organic carbon	mg/L	80–260	Total suspended solid	mg/L	120–400
			Biochemical oxygen demand	mg/L	110–350
			Chemical oxygen demand	mg/L	250–800
			Total coliform	Counts/100 mL	10^6–10^9
			Fecal coliform	Counts/100mL	10^3–10^7

Table 2. Typical nutrients and contaminants in untreated domestic wastewater (based on [15]).

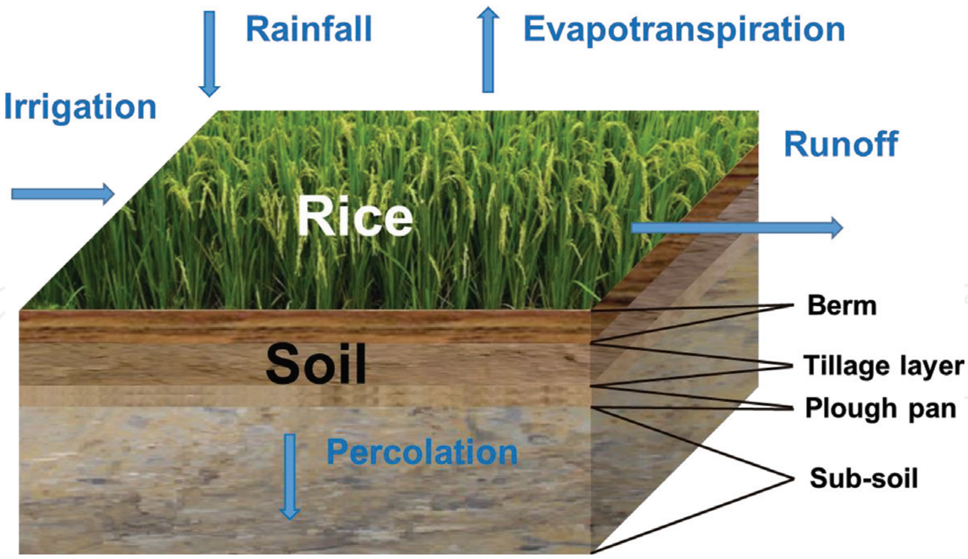

Figure 5. Water budget in rice production.

common, major water input to paddy fields. However, irrigation is usually needed to maintain an appropriate depth of ponding water enclosed by a constructed field berm (**Figure 5**). In addition to evapotranspiration, surface runoff is a major water output from paddy fields. Along with runoff water, phosphorus and nitrogen applied to rice or those in the soil materials are exported from paddy fields. Runoff occurs when the depth of the field ponding water is greater than the height of field berm. Runoff can be generated following small rainfall events when ponding water has been already substantial but more frequently during rainfall storms [16, 17]. Paddy soils are often heavily textured and have a plow pan beneath the surface soil (particularly for long-term cultivated paddy fields). Therefore, the amount of water percolating to the subsoil and out of the root zone is relatively small as compared to surface runoff. Nonetheless, Qiu et al. [18] reported that nitrate-nitrogen concentrations could reach 30–50 mg/L in the leachate from some paddy soils within 1–2 days after fertilizer applications. Due to the flooding nature of paddy fields, the surface soil is often water saturated with a predictably small change in soil water content throughout the paddy growing periods. The anaerobic condition may lead to an elevation of dissolved phosphorus concentrations in runoff water because when iron cation is transformed from $iron^{3+}$ to $iron^{2+}$ under anaerobic conditions, the phosphorous ions bound by $iron^{3+}$ is dissolved. Moreover, artificial drainage that is made to prepare the field (**Figure 4**) forms a direct pathway for nutrient transport to surrounding water environments. Finally, paddy irrigation with nutrient-rich water (such as domestic wastewater; **Table 2**) can also greatly elevate risks of nutrient losses to the water environments.

Phosphorus and nitrogen applied to paddies with fertilizers and manures contribute to both short-term and long-term nutrient losses to the water environments. In a 3-year field study on the hydromorphic paddy soil, for example, Liu et al. [19] found that annual total phosphorus loss in surface runoff ranged from 0.63 kg/ha in the unfertilized rice-wheat rotation to 0.96–2.86 kg/ha when rice and wheat were fertilized with 50–230 kg phosphorus per hectare. In the same study, they found relatively smaller total phosphorus losses from the

Soil	Rice growing season					Wheat growing season			
	Rainfall depth (mm)	Irrigation depth (mm)	Phosphorus rate (kg/ha)	Days between fertilizer application and the first runoff	Total phosphorus loss (kg/ha)	Rainfall depth (mm)	Phosphorus rate (kg/ha)	Days between fertilizer application and the first runoff	Total phosphorus loss (kg/ha)
Hydromorphic paddy	604	833	0	5	0.13±0.01	449	0	10	0.23±0.01
	604	833	30	5	0.19±0.02	449	20	10	0.41±0.03
	604	833	75	5	0.48±0.08	449	40	10	0.64±0.02
	604	833	150	5	0.92±0.06	449	80	10	0.97±0.05
	761	868	0	2	0.76±0.05	688	0	31	0.13±0.01
	761	868	30	2	1.06±0.12	688	20	31	0.21±0.01
	761	868	75	2	2.27±0.31	688	40	31	0.24±0.02
	761	868	150	2	4.18±0.33	688	80	31	0.49±0.03
	531	1290	0	1	0.36±0.06	547	0	14	0.27±0.03
	531	1290	30	1	0.59±0.05	547	20	14	0.43±0.04
	531	1290	75	1	0.93±0.09	547	40	14	0.65±0.07
	531	1290	150	1	1.56±0.19	547	80	14	1.11±0.08
Degleyed paddy soil	548	833	0	58	0.14±0.02	439	0	11	0.26±0.01
	548	833	30	58	0.16±0.01	439	20	11	0.41±0.02
	548	833	75	58	0.23±0.03	439	40	11	1.03±0.04
	548	833	150	58	0.29±0.03	439	80	11	1.31±0.09
	723	868	0	45	0.20±0.04	667	0	32	0.22±0.02
	723	868	30	45	0.32±0.02	667	20	32	0.37±0.02
	723	868	75	45	0.27±0.04	667	40	32	0.51±0.02
	723	868	150	45	0.55±0.09	667	80	32	0.78±0.03
	555	1290	0	49	0.17±0.01	468	0	13	0.18±0.02
	555	1290	30	49	0.23±0.01	468	20	13	0.76±0.19
	555	1290	75	49	0.28±0.01	468	40	13	1.18±0.17
	555	1290	150	49	0.38±0.02	468	80	13	1.39±0.12

Table 3. Phosphorus losses in runoff from a rice-wheat rotation cropping system under different natural and management conditions (mean ± standard error, n = 4 for the hydromorphic paddy soil or 6 for the degleyed paddy soil; adapted from [19]).

degleyed paddy soil that ranged from 0.41 kg/ha in the control group to 0.70–1.49 kg/ha in the treatments with 50–230 kg phosphorus per hectare. Although the differences in magnitude of phosphorus losses in the two soils could result from different soil characteristics and rainfall patterns, both revealed increased phosphorus losses with greater phosphorus fertilizer application rates (**Table 3**). Furthermore, Liu et al. [19] found that the time interval between fertilizer application and the subsequent first large runoff event played a critical role in determining the annual phosphorus losses. Phosphorus losses greatly increased with decreasing time interval. The finding was supported by Guo et al. [20] who claimed that about 40% of total phosphorus loss from a rice-wheat rotation occurred within 10 days after fertilizer application to paddies.

In addition to "incidental" nutrient losses, overuse of fertilizers or manure also constitutes long-term risks of nutrient losses. A number of studies have demonstrated evidential buildup of soil phosphorus status and elevated degree of phosphorus saturation due to long-term phosphorus applications at rates exceeding crop needs [21–23]. In turn, phosphorus losses in surface runoff and leaching have been found to increase with elevated soil phosphorus status or degree of phosphorus saturation [22, 24]. This has been widely referred as legacy phosphorus issues [25]. Even though most of the research on this topic has been conducted on dryland soils, a few studies have reported that long-term excessive application of nutrients could enhance environmental pollution risk in paddy fields [4, 26]. In double cropping systems where flooded rice is planted in rotation with drained dryland crop, we can expect nutrient surplus from both rice and dryland crop-growing seasons [27]. It should be noted that China has the most intensive nutrient use in paddy systems among the world's top 10 rice-producing countries (**Table 4**). Therefore, there is a special need of better water and nutrient management to minimize nutrient losses from paddy systems.

Country	Average yield (Mg/ha)	Nitrogen (kg/ha)	Phosphorus (kg/ha)	Potassium (kg/ha)
China	6.2[#]	145	26.2	33.2
India	2.7	68	10.5	7.5
Indonesia	4.1	105	9.6	11.6
Bangladesh	3.2	72	6.5	8.3
Vietnam	4.1	115	19.6	34.9
Thailand	2.4	62	14.4	14.1
Myanmar	3.2	35	5.2	3.3
Philippines	3.0	51	6.5	9.1
Brazil	3.0	40	21.8	24.9
Japan	5.8	78	40.2	59.7

#: Estimation of rice yield in China is made by the authors of this chapter.

Table 4. Rice yield and nutrient applications to rice in world's major rice-producing countries (data adapted from [28]).

5. Monitoring of water quality in paddy systems

In China, the approach for monitoring water quality in paddy systems has become standardized over the past 2 decades [12, 19, 29]. In the field, research plots are separated with plastic films down to 0.9 m in the soil profile and with soil berms up to 0.2 m on the soil surface to prevent flow of surface and shallow subsurface water between the plots (**Figure 6**). Soil berm is a common practice to maintain field ponding water for rice production. During the rice-growing season, irrigation water is applied to individual plots through polyvinyl chloride pipe inlets when needed. During the non-rice crop-growing season in a double-cropping system, irrigation is usually not applied. Excessive ponding water is drained through shallow open ditches. Outside each plot on the opposite side of the irrigation water inlet, a cement pond is constructed to collect runoff water from every plot. Two water outlets of polyvinyl chloride pipe are installed on the wall of the cement pond, at depths of approximately 10 cm above and 10 cm below the soil surface, for collecting runoff water during the rice-and wheat-growing seasons, respectively. The runoff water collected in the pond is measured for volume and sampled for analyses of nutrients and sediments. Usually, one sample is taken after every regular runoff event and multiple samples during a large runoff event (i.e., rain storms).

Even though the approach described earlier is widely used such as in a national program to estimate nutrient losses from paddy systems across China, there has been an increasing interest in seeking alternative, simplified monitoring approaches. One potential approach is to monitor nutrient concentrations in the field ponding water. Liu et al. [19] found that concentrations of both total phosphorus and dissolved reactive phosphorus in surface runoff were significantly correlated with their concentrations in the field ponding water (r^2 = 0.83–0.88, $p < 0.0001$). In a follow-up study, Hua et al. [27] monitored different forms of phosphorus concentrations in field ponding water of five paddy soils over 2 years. They found that 2 weeks after fertilizer application is a critical period for phosphorus loss from paddies, which supported findings of others [19, 20]. Despite the large potential of monitoring field ponding water to save a lot of work associated with constructing runoff collection facilities, it should be

Figure 6. Monitoring of water quality in paddy systems: Research plots and field ponding water on the left and runoff collection facility on the right.

noted that this approach would not give information on runoff volume, and it is not practical for dryland crops. Further research is needed with respect to achieving cost-effective monitoring methodologies.

6. Mitigation options to improve water quality in paddy systems

In China, paddy systems are attributed to an important cause for local and regional water eutrophication (e.g., [4, 5]). Both its wide distribution and intensive nutrient and water inputs point to the need for improved management to minimize its impacts on water quality. A number of studies have emphasized the importance of adopting “4R” nutrient stewardship, i.e., Right source, Right rate, Right timing, and Right placement in paddy systems (e.g., those summarized in **Table 5**). For example, Fujisawa et al. [30] proposed the use of thermoplastic resin-coated fertilizers that allow the application of the fertilizers at full rates to rice seedlings and thereafter the release of nutrients in line with crop needs. Liu [31] found that adopting this technology could substantially increase nitrogen use efficiency by the rice crop as compared to the urea fertilizer and conventional management practices. The technology decreased peak nitrogen concentrations in field ponding water by 85–91%, postponed the appearance of peak concentrations by a week, and reduced total nitrogen (nitrate nitrogen plus ammonium nitrogen) losses in leachate by 36–55%. As discussed earlier, overuse of fertilizers should be avoided because the nutrient surplus contributes to both short-term and long-term nutrient losses. Liu et al. [19] and Hua et al. [27] pointed out that phosphorus fertilizer applications to paddy systems should be at rates balancing crop phosphorus removal, and that phosphorus needs to be managed for both rice and the non-rice crop in a rotation to minimize phosphorus losses in the rice-growing season. Fertilizer rate management should go hand in hand with management of fertilizer application timing. Planning fertilizer timing based on local/regional weather patterns and real-time weather forecast to avoid coincidence with rainfall storms is an important timing management approach [19, 20]. In the regions where the coincidence of fertilizer application and rainfall storm is difficult to avoid, one of the optional management practices

Category	Mitigation options	References
Nutrient management	Use slow-release fertilizer and apply all fertilizers at the seedling stage	Fujisawa et al. [30]; Liu et al. [31]
	Reduce fertilizer application rate	Liu et al. [19]; Hua et al. [27]
	Avoid fertilizer application during rainstorm period; split and reduce basal fertilizer dose	Guo et al. [20]; Liu et al. [31]; Liu et al. [19]
	Apply fertilizer as side bars	Yang and Yang [32]
Water management	Alternate drying and wetting	Peng et al. [33]
	Control irrigation and drainage water volume	Zhang et al. [5]; Gao et al. (2017)
	Control irrigation water quality	

Table 5. Mitigation options to improve water quality in paddy systems.

might be to split fertilizer to multiple doses and reduce the dose of basal fertilizers [31]. Furthermore, Yang and Yang [32] suggested applying fertilizers as side bars close to paddy roots, which could significantly increase nutrient use efficiency and reduce losses as compared with broadcasting the fertilizers.

Water management is also of great importance to reduce nutrient losses from paddy fields to surrounding water bodies. In a field study in China's Taihu Lake Region, Peng et al. [33] found that adopting an alternate drying and wetting technology reduced total phosphorus losses by up to 52% in surface runoff and 55% in subsurface drainage across an array of nutrient management practices, as compared to the conventional irrigation and drainage management. Zhang et al. [5] proposed a "zero-drainage water management" approach, which used natural field drying to replace conventional surface drainage based on the physiological water need for rice growth. They found that a combination of improved irrigation and field drying based on rainfall forecasting eliminated all drainage and phosphorus export from paddy fields (0.65 kg/ha under conventional management), while successfully meeting the physiological water requirement of plant growth. Elsewhere, Gao et al. [34] also found that appropriate control of irrigation and drainage could significantly reduce nitrogen and phosphorus concentrations in the field ponding water. Furthermore, when irrigation water is rich in nutrients such as in the scenario of wastewater irrigation [15], control of irrigation water quality is necessary to reduce paddy nutrient release to the water environments. Potentially, nutrient management practices and water management practices should be combined to achieve most desirable water quality outcomes and a sustainable agroecosystem.

7. Conclusions

Grand challenges exist in improving water quality in paddy systems. China is the largest rice-producing country in the world and also has the most intensive use of nutrients and water in rice production. Challenges to minimize the impacts of paddy nutrient losses on the water environment in China are even greater than anywhere else. Past research related to paddy systems has proved the importance of nutrient and water management on improving water quality. A combination of management in nutrient source, rate, timing and placement, and management in irrigation and drainage of water shows a great potential to reduce nitrogen and phosphorus losses from paddy fields. Even so, more research is needed to identify cost-effective monitoring approaches and mitigation options. Furthermore, extension and policy enforcement is needed beyond research to achieve water quality goals. Nonetheless, it should be noted that management of paddy water quality needs to be placed in a larger context of environmental protection. Our ongoing work has estimated that nutrient loss from paddy fields is smaller than that from intensively managed non-paddies such as vegetable fields. In some regions with high nutrient concentrations in surface water, paddy fields have even smaller nutrient losses in surface runoff than the nutrient inputs to the fields through irrigated and precipitated water.

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