

Characteristics of rural domestic wastewater with source separation

Fangkui Cheng, Zheqin Dai, Shuting Shen, Siyu Wang and Xiwu Lu

ABSTRACT

Rural domestic wastewater (RDW), one of the non-point pollution sources, has become a significant object related to sanitation improvement and water pollution control in Taihu Lake Basin, China. Current research on RDW characteristics and management with source separation is limited. In this study, a source-separated investigation into the characteristics of RDW was conducted, and the management suggestions were proposed. The results showed that the average RDW production coefficient was 94.1 ± 31.6 (range: 71.8–143.0) liters per capita (person) per day. Household-level wastewater generation peaked two or three times daily, and the synchronous fluctuation could cause hydraulic loading shocks to treatment facilities. The population equivalents of chemical oxygen demand, ammonium nitrogen (NH_4^+-N), total nitrogen (TN), and total phosphorus (TP) in RDW were 78.7, 3.7, 4.12, and 0.8 g/(cap·d), respectively. Blackwater from water closet source accounted for 30.4% of the total wastewater amount, contributing 93.0%, 81.7%, and 67.3% to loads of NH_4^+-N , TN, and TP, respectively. Graywater from the other sources with low nutrient-related pollutant concentrations and loads, accounting for 69.6% of the total wastewater amount, was a considerable alternative water resource. The quantitative and qualitative characteristics indicated that GW and BW had the potential of being reused in relation to water and nutrients, respectively.

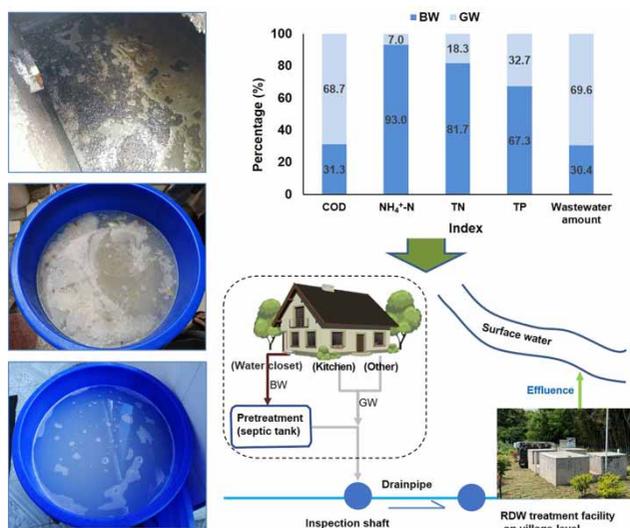
Key words | generation characteristic, pollution load, production coefficient, rural domestic wastewater, source separation

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HIGHLIGHTS

- A novel source-separated investigation into rural domestic wastewater (RDW) was conducted.
- The population equivalents of water amount and pollutant loads in RDW were obtained.
- GW and BW in RDW had the potential for reuse in relation to water and nutrients, respectively.
- A village-level RDW management mode considering wastewater source separation was proposed.

GRAPHICAL ABSTRACT



ABBREVIATIONS

RDW	rural domestic wastewater
UDW	urban domestic wastewater
BW	blackwater
GW	graywater
H1	Household 1
H2	Household 2
H3	Household 3
H4	Household 4
H5	Household 5
COD	chemical oxygen demand
NH ₄ ⁺ -N	ammonium nitrogen
TN	total nitrogen
TP	total phosphorus

INTRODUCTION

The rapid economic development in China's rural areas brings enormous living improvement and tremendous environmental pollution. The annual wastewater discharge in China has exceeded 75 billion tons till now, of which the urban domestic wastewater (UDW) accounts for about 41% and rural domestic wastewater (RDW) for approximately 26%, according to the annual China Statistical

Yearbooks on Environment (NBS 2016). Only 11.4% of the RDW has been treated, compared to that of UDW (91.9%) (Cheng *et al.* 2018; Ding *et al.* 2019) and, as a result, the amount of untreated RDW was nearly seven times more than the untreated UDW. The amount of untreated RDW is directly discharged into rural areas has increased, imposing a significant threat to the aquatic environment. It can cause eutrophication, black-odor, and increased pathogenic bacteria in rural area water bodies. Fortunately, RDW management has received intense focus in recent years for both water reuse and pollution control.

Different strategies and techniques can be applied for RDW management: source control (Gao *et al.* 2019a), physical-chemical (Ding *et al.* 2019), biological (Zha *et al.* 2018), as well as ecological (Sylla 2020) techniques. A large number of treatment scenarios can be formed by combining these methods, each with various applicable conditions. However, those studies only focused on efficiency improvement for the separated blackwater treatment or the end-of-pipe wastewater treatment, and they did not consider the pre-treatment with source separation at the household level or village-level based on the characteristics of RDW. The characteristics of the wastewater are the essential parameters influencing the appropriate selection of a scenario (Yin *et al.* 2010). Moreover, the quantitative characteristics

of RDW, such as the graywater (GW) proportion (Ghaitidak & Yadav 2013), could represent the potential of low-cost onsite reuse (Alsulaili & Hamoda 2015). The qualitative characteristics, such as concentrations and loads distribution of nutrient-related pollutants, could be used in environmental pollution prediction and resource recovery capacity assessment. Detailed source-sorted information will help to find out the challenges and opportunities of RDW treatment and guide the management of RDW in the future. The challenges may be the household-level source-separated drainage pipeline modification and the supplement of pretreatment facilities for separated wastewater in the rural household. However, source-separated feature identification could guide the more efficient treatment for the separated sources, achieve less operation and maintenance costs in the whole RDW management process, and realize reasonable resource recovery from different sources. Thus, figuring out the characteristics of RDW is the foundation stone of its management.

Although many studies (Hong-bin *et al.* 2010; Nsavyimana *et al.* 2020) have been carried out for UDW identification, the characteristics results cannot be applied to RDW because the habits of water utilization and washing compositions in urban and rural areas differ. Further, UDW characteristics are usually investigated on a community-scale with a dense population in a vast region (Sharma *et al.* 2016). However, the features or characteristics of the RDW from individual households are important due to the sparse population, terrestrial complexity, and lack of pipeline (Hong-bin *et al.* 2010). Consequently, it is necessary to look into the generation sources (e.g. kitchen and water closet (WC), etc.) in single households during RDW identification. However, very few studies on the characteristics of RDW have been conducted at the household level and even less on household source separation.

Previous studies (Eriksson *et al.* 2002) have provided a detailed municipal sewage classification and proposed numerous classification methods. Commonly, domestic wastewater is classified according to the level of pollutant concentration and load. The characteristics of UDW from different sources in China have been investigated (Hong-bin *et al.* 2010), and the classification methods of blackwater (BW; from WCs) and integrated GW (from all other sources) have been suggested. The kitchen wastewater was classified as GW. However, in another study (Alsulaili & Hamoda 2015), the kitchen wastewater was advised not to be included in GW. In other words, the classifications of wastewater sources were divergent in previous studies. A further source-separated investigation of RDW should be conducted to figure out the source characteristics and categories.

This paper, which initiated an investigation into the RDW characteristics from the perspective of source separation, is aimed at exploring its potential in water conservation and resource recovery and providing suggestions for future village-level management of RDW. RDW in Taihu Lake Basin was studied as an essential supplementary of domestic wastewater. The population equivalent of water amount and pollution loads in RDW were investigated in this study. This source-separated study can guide the management of RDW in rural China. The 'Materials and methods' describes the targeted sample households in the Taihu Lake Basin, the method used to collect composite samples from WC, kitchen, and other sources in each household, the method used to test the samples' pollution indexes, and analytical methods. The 'Results and discussion' represents the source-separated wastewater generation rates and pollutant concentrations and loads, as well as suggestions for RDW management derived from the results.

MATERIALS AND METHODS

Research area and object selection

As RDW is one of the three primary non-point pollution sources (along with planting and breeding) in rural areas, it has significantly contributed to pollution in Taihu Lake. This research was conducted in this typical lake basin (Figure 1(a) and 1(b)).

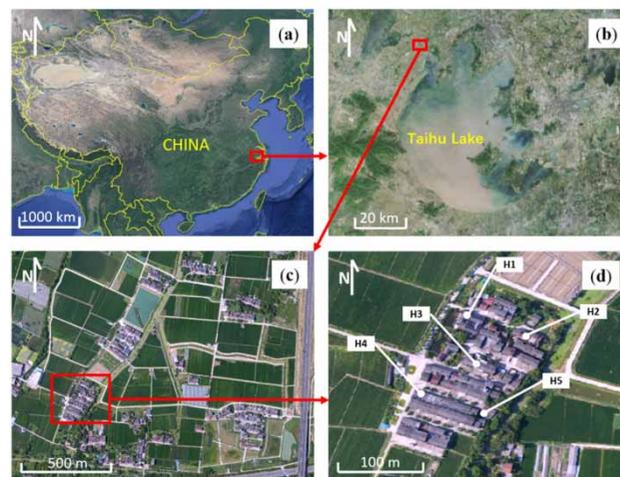


Figure 1 | Distribution of villages and the layout of the researched natural village located in Taihu Lake Basin, China. (a) Location of Taihu Lake Basin, (b) Taihu Lake Basin, (c) distribution of villages, and (d) the layout of Wangjiatang Natural Village and distribution of five sample households.

The distance between natural villages is several hundred meters (Figure 1(c)), while the residential buildings inside villages are relatively dense (Figure 1(d)) in the rural areas of Taihu Lake Basin. This is a distinctive geographical distribution feature of villages in this basin, and is an essential factor affecting RDW management. It would be expensive to conduct a long-distance pipeline for collecting wastewater among villages. An individual natural village with centralized households was conventionally taken as a basic unit of decentralized RDW treatment. Therefore, this case investigation on the generation characteristics of RDW was conducted in a representative natural village, i.e. Wangjiatang Natural Village (119.99399°E, 31.53899°N; Figure 1(c)) in northwestern Taihu Lake Basin. Wangjiatang Natural Village has 53 residential households, and five were selected as sample households (i.e. H1, H2, H3, H4, and H5; Figure 1(d)) by the five-point sampling method. The basic information (i.e. household number, family size, water sources, wastewater generated from sites, and water volume from WC flushing) of the sample households are shown in Table 1.

Source-separated collection and monitoring of RDW

Since the classification of kitchen wastewater in RDW was controversial, the kitchen wastewater was collected and measured separately to verify its characteristics and determine its classification for this study. Therefore, in this research methodology, rural household wastewater was divided into three parts: (1) WC wastewater (from WCs for flushing feces and urine; Figure S1(a) and S1(b) in

the Supplementary Material), (2) kitchen wastewater (from washing food and kitchenware; Figure S1(c) and S1(d)), and (3) other wastewater (from washing, showering, bathing, laundering, and so on; Figure S1(e) and S1(f)). The kitchen and other wastewaters from each sample household were collected separately in 160-L plastic buckets with lids and scales (accuracy: 0.1 L) for collecting volume data. Each WC had fixed water volumes for flushing feces or urine (Table 1). Every instance and category (i.e. for feces or urine) of flushing for each sample household was recorded to calculate the WC wastewater volume, rather than directly monitoring the outflow volume. The wastewater volume of these three categories was separately counted every 2 h of a sample day. The daily study was repeated 15 times in four consecutive seasons (i.e. 3–4 sampling days per season) from 16 September 2018 to 20 July 2019.

Sampling and testing

The wastewater collected in buckets was stirred and mixed, and an integrated sample was obtained at 24:00 every sampling day. Each sample was sealed in a 0.25-L polyethylene bottle to prevent contamination and damage. Samples were stored at 4 °C and transported for analysis to the analytical laboratory at Southeast University within 24 h. To ensure hygiene and feasibility, WC wastewater was not collected in containers. All households involved in the study were equipped with septic tanks, and when the rest of the wastewater had been collected in containers, the only wastewater that entered the septic tank through the

Table 1 | General information on sample households involved in this research

Household no.	Family size (capita)	Water sources	Wastewater generated from sites	WC flushing water volume (L)
H1	3	Well and tap water	The WC, washbasins, kitchen sinks, shower, bathtub, washing machine	7.5 (for feces), 4.0 (for urine)
H2	2	Well and tap water	The WC, washbasins, kitchen sinks, shower, bathtub, washtub	10.0 (for feces), 6.0 (for urine)
H3	2	Well and tap water	The WC, washbasins, kitchen sink, shower, bathtub, washing machine	10.0 (for feces), 6.0 (for urine)
H4	2	Well and tap water	The WC, washbasins, kitchen sinks, shower, bathtub, washtub	10.0 (for feces), 5.0 (for urine)
H5	4	Well and tap water	The WC, washbasins, kitchen sinks, shower, bathtub, washing machine	6.0 (for feces), 3.6 (for urine)

household drainage pipes was from the WC source. The septic tanks were drained and cleaned in advance of WC wastewater collection. Mixed wastewater samples were collected from the septic tanks using the above-mentioned sample container at the end of each sample day.

Chemical oxygen demand (COD), ammonia nitrogen ($\text{NH}_4\text{-N}$), total nitrogen (TN), and total phosphorus (TP) concentrations of all wastewater samples were tested by fast digestion–spectrophotometric method, Nessler’s reagent spectrophotometry, alkaline potassium persulfate digestion UV spectrophotometric method, and ammonium molybdate spectrophotometric method, respectively, according to the standard method (APHA 2012).

Statistical analysis

The statistical analysis was carried out using SPSS software (IBM Corporation, USA) and the OriginPro 2018b software (OriginLab Corporation, USA). Mann–Whitney U-test ($P < 0.05$ significant level) was used to identify the average daily total wastewater pairwise seasonal differences. One-way analysis of variance (ANOVA) ($P < 0.05$ significant level) was used to determine the statistically significant differences in multi-group wastewater production of different periods.

RESULTS AND DISCUSSION

Quantitative characteristics of RDW generation

The quantitative characteristics provide an essential basis for domestic wastewater management and treatment. For example, they act as a reference for setting the scale of treatment facilities, which partly determines the investment required. Investment is the most significant factor hindering RDW treatment in developing countries, including China. Therefore, studying the generation rate of household wastewater in natural villages is vital. Hence, the wastewater produced by five sample households in Wangjiatang Natural Village for 15 sample days in a year was classified, collected, and measured for three categories (i.e. WC, kitchen, other sources). The statistical analysis results on the generation rate of sample household wastewater with source separation are shown in Figure 2. The average total wastewater generation rate of the sample households was 94.1 ± 31.6 L/(cap-d), and varied in the range of 71.8–143.0 L/(cap-d) (detailed data is listed in Table S1 of the Supplementary Material), which was

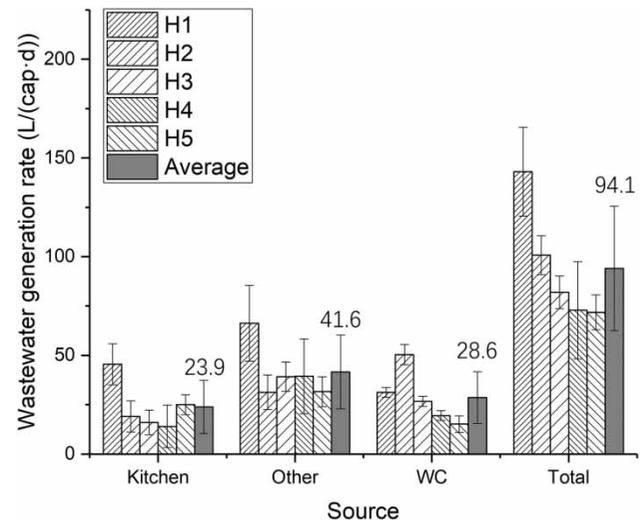


Figure 2 | The generation rate of three types (i.e. kitchen, WC, other sources) and the total (i.e. sum of kitchen, WC, other sources) wastewater of the sample households (i.e. H1, H2, H3, H4, and H5).

considered to be the production coefficient of RDW. According to the China National Standard of Water Quantity for daily residential use in cities, the research area’s domestic water consumption ranged between 120 and 180 L/(cap-d). When the wastewater production ratio was set to 0.8, the residents could generate 108–144 L/(cap-d) of wastewater. The RDW production coefficient was close to the lower limiting value. This result also reflects that the domestic sanitation facilities (Table 1) in this rural area are close to those in the urban area since the production coefficient is generally influenced by the household sanitation facility’s development level.

As shown in Figure 2, the generation rates of household wastewater from WC, kitchen, and other sources were 28.6 ± 13.1 (range: 15.2–50.4), 23.9 ± 13.5 (range: 14.0–45.5), and 41.6 ± 18.7 (range: 31.3–66.3) L/(cap-d), accounting for 30.4%, 25.4%, and 44.2% of the total generation rates, respectively (shown in Table S1 in Supplementary Material). By comparing the standard deviation of the three types of wastewater generation rates in each sample household (i.e. other sources > kitchen > WC; Table S1), it could be determined that the variations in WC wastewater production were smallest, which is mainly due to the constant single flushing water volume and stable daily use frequency of WCs.

In the previous study of UDW (Hong-bin *et al.* 2010), wastewater from WCs was identified as BW, and the other wastewater was categorized as GW. Using this

classification method, the volume ratio of BW; GW in this RDW study was approximately 3:7. The proportion of BW in UDW reported in literature ranged from 12 to 33% (Thibodeau *et al.* 2014; Jin *et al.* 2018); thus, the proportion of BW in RDW is relatively high. This ratio is closely related to the WC single-flush water volume. The WCs in the sample households are all set to the dual-volume mode, with a flushing capacity of 3.6–10.0 L water/flush (Table 1), while the reported vacuum toilet could consume 0.5–1.2 L water/flush (Gao *et al.* 2019b). This suggests that there is room for saving water in WCs in this study. If water-saving WCs are used in place of conventional WCs, the amount of BW could be reduced (Gao *et al.* 2019b). Reducing the amount of WC flushing water could increase the concentration of pollutants in BW and improve subsequent sewage treatment (Florentino *et al.* 2019). Therefore, reducing the flushing water volume of household WCs should be considered in the future management of RDW in the Taihu Lake Basin. This measure would effectively contribute to the total RDW amount reduction.

According to the results above mentioned, the GW volume was 65.4 ± 21.2 L/(cap-d) and accounted for 67.8% of the total (i.e. 94.1 ± 31.6 L/(cap-d)). Some published figures on the residential GW generation rate in different regions of the world are listed in Table 2. The generation of GW varies widely among different countries and regions. In developing areas (e.g. Yemen, India, Jordan, South Africa, Senegal), the GW generation rate ranges from 35

to 80 L/(cap-d), while those of developed areas (e.g. North America, USA, England, and Wales) are in a much higher range of 96–200 L/(cap-d). Meanwhile, some researchers have also found a significant relationship between wastewater generation and economy level (Ding *et al.* 2019). The GW generation rate (65.4 ± 21.2 L/(cap-d)) in this study is in the range of developing areas. This demonstrates that there is potential to improve the GW generation rate in the research area in line with the developing economy. RDW management in future should be aware of this characteristic. Researchers have pointed out that the proportion of GW in domestic wastewater determines the potential for reuse in feasibility and economic efficiency. With a proportion of only 15%, GW was even recommended to be reused (Alsulaili & Hamoda 2015). With a proportion of 67.8%, the GW in RDW in this research area is eligible for water resource recycling in terms of the quantity characteristic.

Temporal variation characteristics of household wastewater generation

The quantity of wastewater from the sample households was measured every 2 h for 15 sample days. The amounts of three types of wastewater generated from the sample households in different periods are shown in Figure 3. The total amount of wastewater generated in sample households in different periods of a day is shown in Supplementary Material Table S2. The sample households mainly generated wastewater between 04:00 and 22:00. In other words, the generation of household wastewater had a significant pause period (i.e. 22:00–04:00 of the next day). Meanwhile, the amount of wastewater significantly differed (ANOVA, $P < 0.05$) between different periods. The temporal distribution of wastewater production was directly related to the daily routines of the families. For example, a full-time housewife lived in Household 1 (H1), and so specific amounts of wastewater were produced throughout the day. Two family members living in Household 3 (H3) were employees of a nearby factory; therefore, there was no domestic wastewater generated during working hours (i.e. 08:00–10:00 and 14:00–16:00). The amounts of wastewater generated from different households significantly differed (ANOVA, $P < 0.05$), even during the same period. For example, the mean amounts of wastewater produced by the five sample households varied from 7.1 to 83.3 L/cap from 04:00 to 06:00 (shown in Table S2), and the maximum value was over ten times the minimum value. In summary, there were significant differences in the temporal

Table 2 | GW generation rate in different regions of the world

Status	County or region	Generation rate L/(cap-d)	Reference
Developed regions	North America	196	Ghaitidak & Yadav (2013)
	USA	200	Alsulaili & Hamoda (2015)
	England and Wales	96	Ghaitidak & Yadav (2013)
Developing regions	South Africa	80	Ghaitidak & Yadav (2013)
	Senegal	60	Ghaitidak & Yadav (2013)
	Jordan	59	Jamrah <i>et al.</i> (2006)
	India	79	Ghaitidak & Yadav (2013)
	Yemen	35	Ghaitidak & Yadav (2013)

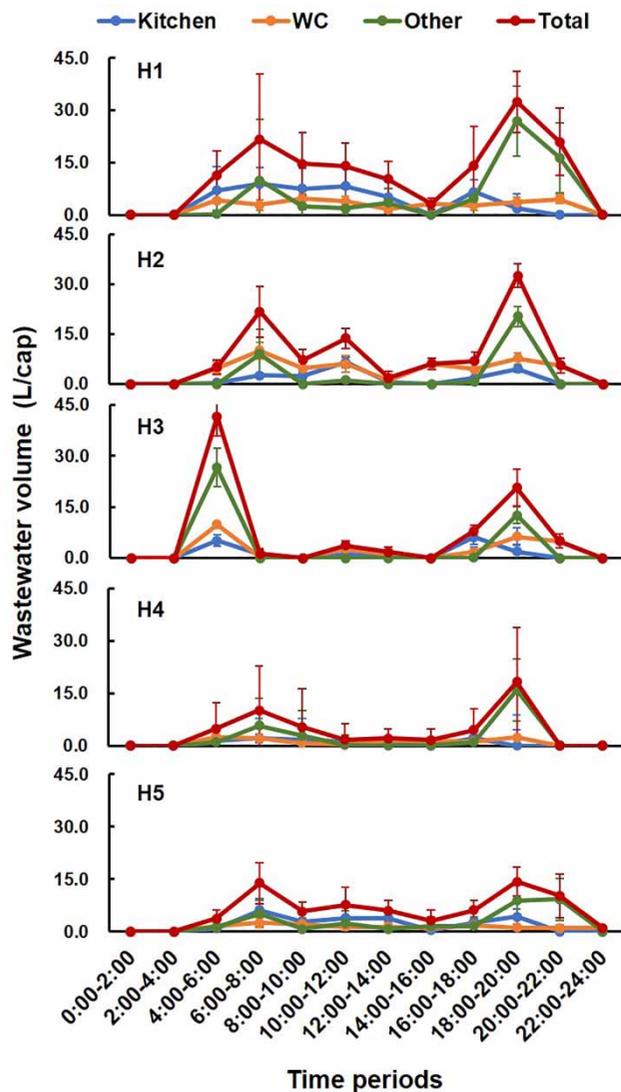


Figure 3 | The daily temporal fluctuation of the generation of three types (i.e. kitchen, WC, other sources) and the total (i.e. sum of kitchen, WC, other sources) wastewater from the five sample households. Household daily wastewater generation statistics of different time periods were calculated for 15 sample days, and each point on the line chart was the mean of the 15 samples.

distribution of domestic wastewater generation between rural households.

The daily temporal variations in the amount of WC, kitchen, other sources, and total wastewater from each household are shown in Figure 3. The line representing the 'other' category exhibited a more extensive range than those of the lines representing kitchen and WC wastewater generation for each household. Furthermore, the lines representing the total amount of wastewater generated by each household had two or three peaks appearing at 06:00–08:00, 10:00–12:00, and 18:00–

20:00. In previous community wastewater studies (Kim *et al.* 2009), such peaks occurred two or three times per day due to household activities, indicating that the daily temporal variation of RDW was similar to that of urban areas. The peaks of the total amount of wastewater were accompanied by those of the 'other' category wastewater, which exhibited more massive peaks than kitchen or WC wastewater. This indicates the 'other' wastewater category mainly dominated the appearance of peaks for total domestic wastewater. According to the information on a local daily-life questionnaire, the frequency and time of the sample families' daily wastewater production peaks were consistent with cooking activities. Although the total wastewater production peaked simultaneously as cooking activities, the contribution rate of cooking (i.e. kitchen) wastewater was low. This can suggest that the cooking time was correlated with other household wastewater production activities and that the kitchen was not the most direct or most massive contributor to the total wastewater production. As shown in Table S1 in the Supplementary Material, the percentage of the 'other' category in the total domestic wastewater output was highest, reaching 44.2%, and was mainly generated during two or three periods. Therefore, the concentrated production of the 'other' category wastewater explained the fluctuation in the total amount of household wastewater generation.

There were definite pause period and peak hours for daily household wastewater production, and these pause periods and peak hours were similar between different households (shown in Figure 3). As a result, hydraulic load shocks caused by the simultaneous wastewater generation during pause and drainage peak hours of the households were common. A natural village is often taken as the unit for RDW treatment, and a small-scale pipe network is constructed to collect household wastewater. Thus, pipeline transportation distance will be short. For example, the natural village's longest pipeline transportation distance in this study was only 185 m. Therefore, the wastewater flow remained in the pipe network for a short time, and so the collection and transportation process has limited water flow regulating capacity. In the management of RDW, the hydraulic loading shocks caused by water flow fluctuation is an issue that needs attention.

In this study, the 15 sampling days were distributed throughout four consecutive seasons. A Mann–Whitney U-test for seasonal comparison of the average daily total wastewater amount for the four seasons was carried out (shown in Table S3 and Table S4 in Supplementary

Material). The results indicated that there were no significant differences ($P > 0.05$) between different seasons in RDW generation. However, there were only three or four sampling days per season. Further studies with more observations should be carried out to make a convincing conclusion on the seasonal fluctuation of RDW.

Pollutant concentration characteristics

Daily household wastewater in three categories (i.e. WC, kitchen, and other sources) was collected, and a composite sample of each category was collected and tested daily. The daily wastewater quality indices monitored were the concentrations of COD, $\text{NH}_4^+\text{-N}$, TN, and TP, and the results are shown in Figure 4.

The mean concentrations of COD, $\text{NH}_4^+\text{-N}$, TN, and TP in WC wastewater were $1,127.7 \pm 228.4$ mg/L (range: 883.1–1,554.5), 106.3 ± 49.1 mg/L (range: 36.5–140.5), 119.3 ± 52.1 (range: 44.3–173.4), and 23.3 ± 10.2 mg/L (range: 9.2–38.7). In kitchen wastewater, the concentrations were 957.4 ± 219.5 mg/L (range: 648.5–1,165.0), 3.3 ± 0.7 mg/L (range: 2.2–4.3), 9.0 ± 2.1 mg/L (range: 7.4–13.0), and 6.7 ± 2.8 mg/L (range: 3.5–11.1), respectively. In the other wastewater, the concentrations were 708.2 ± 100.9 mg/L (range: 591.6–880.7), 2.5 ± 0.5 mg/L (range: 2.0–3.5), 10.9 ± 5.6 mg/L (range: 3.9–19.1), and 2.3 ± 2.6 mg/L (range: 0.4–7.3), respectively (as shown in Table S5 in Supplementary Material). As seen in Figure 4, the COD, $\text{NH}_4^+\text{-N}$, and TP concentrations decreased in the following order: WC > kitchen > other. Meanwhile, the TN concentrations decreased in the order of WC > other > kitchen. The four pollutant indices were all

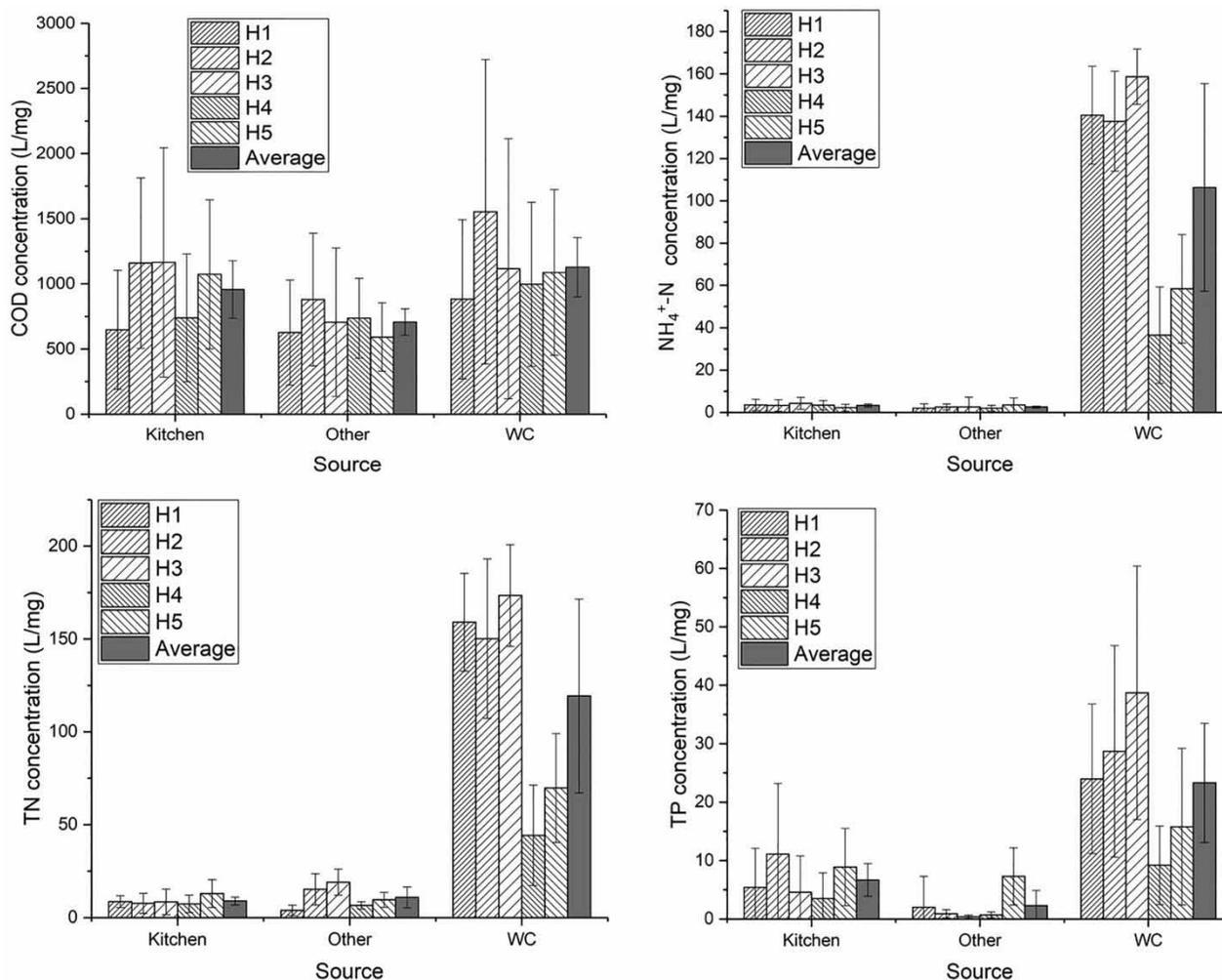


Figure 4 | Pollutant concentrations of three wastewater sources (WC, kitchen, and other) from five sample households. Samples were collected and tested for 15 sample days ($n = 15$).

highest in wastewater from WCs, and those related to nutrients (i.e. N and P) in WC wastewater were higher than those in the other two types of wastewater. For instance, the concentrations of N-related pollutants (i.e. $\text{NH}_4^+\text{-N}$ and TN) in WC wastewater were more than ten times those in wastewater from the other two sources. The mean concentration of TP in WC was 3.5 times and 10.1 times that in the kitchen and other sources, respectively.

Previous studies suggest that the kitchen's wastewater should not be classified as GW (Alsulaili & Hamoda 2015); however, some researchers insisted that it should belong to dark GW (Ghaitidak & Yadav 2013). Since pollutant concentrations of kitchen sewage in this RDW study are different from those of WC and similar to those of 'other', we suggest that WC flushing water with higher contaminants should classify as BW. On the contrary, the other categories with lower and similar concentrations of contaminants should classify as GW.

Characteristics of pollution loads distribution in RDW

The daily total amount of one type of wastewater generated from the sample households can be multiplied by the pollutant's concentration to calculate the amount of pollutant generated (i.e. pollution load). The pollution load values and proportions of each wastewater source are shown in Table 3. The COD pollution loads of the three types of wastewater all exceeded 20.0 g/(cap-d), and the pollution load proportions all exceeded 30.0%. The COD pollution loads and proportions of the three types of wastewater

were similar. The pollution load values and proportions of the $\text{NH}_4^+\text{-N}$, TN, and TP loads in WC wastewater were 2.5, 2.8, and 0.5 g/(cap-d), and 93.0%, 81.7%, and 67.3%, respectively, which were all higher than those in the other two types of wastewater. Therefore, from the perspective of the pollution load value and proportion, WC wastewater in RDW should still be classified as BW, and the remainder classified as GW.

According to the wastewater classification method based on the water quality characteristics proposed above, the distribution of the pollution loads of COD, $\text{NH}_4^+\text{-N}$, TN, and TP, in GW and BW was statistically analyzed, and the results are shown in Figure 5.

The COD load percentages in GW and BW of RDW were 68.7% and 31.3%, respectively. The reported COD load percentage of GW in UDW was only 49% (Luostarinen et al. 2007), reflecting that GW played an important role in organic material production in RDW. The COD load of GW (i.e. COD load of kitchen and other sources, in Table 3) divided by the water amount of GW (i.e. water amount of kitchen and other sources in Table S1) equals the COD concentration in GW (i.e. 718.6 mg/L). The COD concentration of the wastewater from WC (i.e. 1,127.7 mg/L in Table S5) represents the COD concentration in BW. In this RDW study, the COD concentration in BW is only 1.6 times that of GW. However, a previous UDW study (Al-Shayah & Mahmoud 2008) indicated that the COD concentration in BW (i.e. 900–1,500 mg/L) was several times that in GW (i.e. 210–740 mg/L). This suggests that indicated the COD concentration of GW in RDW was

Table 3 | Values and proportions of the pollution loads of three RDW sources in the sample households

Source	Index	Pollution load (g/(cap-d))					Average (g/(cap-d))	Percentage (%)
		H1 ^a	H2 ^a	H3 ^a	H4 ^a	H5 ^a		
WC	COD	28.2 ± 20.6	80.9 ± 63.0	30.76 ± 28.3	10.6 ± 5.9	16.2 ± 10.6	21.4	31.3
	$\text{NH}_4^+\text{-N}$	4.4 ± 0.7	7.0 ± 1.6	4.31 ± 0.7	0.4 ± 0.3	0.9 ± 0.5	2.5	93.0
	TN	5.0 ± 0.8	7.6 ± 2.5	4.71 ± 1.0	0.5 ± 0.3	1.0 ± 0.6	2.8	81.7
	TP	0.8 ± 0.4	11.0 ± 0.7	0.93 ± 0.7	0.1 ± 0.1	0.2 ± 0.2	0.5	67.3
Kitchen	COD	30.0 ± 22.0	21.8 ± 12.2	19.1 ± 16.3	6.1 ± 8.6	27.3 ± 16.7	20.5	30.0
	$\text{NH}_4^+\text{-N}$	0.2 ± 0.2	0.1 ± 0.1	0.07 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	0.1	3.1
	TN	0.4 ± 0.2	0.2 ± 0.1	0.14 ± 0.1	0.1 ± 0.1	0.3 ± 0.2	0.2	6.8
	TP	0.3 ± 0.4	0.1 ± 0.2	0.07 ± 0.1	0.0 ± 0.0	0.2 ± 0.2	0.2	20.0
Other	COD	37.8 ± 22.0	27.9 ± 15.7	29.1 ± 23.8	20.4 ± 12.9	18.6 ± 9.1	26.5	38.7
	$\text{NH}_4^+\text{-N}$	0.1 ± 0.2	0.1 ± 0.1	0.10 ± 0.2	0.1 ± 0.1	0.1 ± 0.1	0.1	3.9
	TN	0.3 ± 0.3	0.5 ± 0.3	0.79 ± 0.3	0.2 ± 0.1	0.3 ± 0.2	0.4	11.5
	TP	0.1 ± 0.3	0.0 ± 0.0	0.01 ± 0.0	0.0 ± 0.0	0.2 ± 0.2	0.1	12.7

^aColumn data are the averages and their standard deviations ($n = 15$).

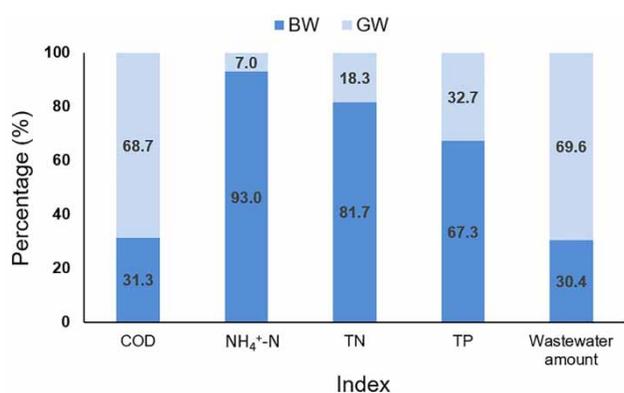


Figure 5 | Distributions of pollutants (COD, NH₄⁺-N, TN, TP) loads and water amount in GW and BW.

relatively high compared to that of UDW. High COD concentration and load may lead to limitations for future reuse of GW in RDW, although it has potential in terms of the water amount.

The percentages of nutrient-related pollution loads (i.e. NH₄⁺-N, TN, and TP) in BW were higher than those in GW. GW's contribution rates to the total loads of NH₄⁺-N, TN, and TP in RDW was only 7.0%, 18.3%, and 32.7%, respectively. The nutrient-related pollution loads distribution in BW and GW was quite similar to those (i.e. 10–20% nutrients in GW) reported in the literature (Shaikh & Ahammed 2020). In other words, BW was the primary source of the nutrient pollution load in RDW. The areas of Taihu Lake Basin, that make up the RDW should be treated differently based on its source. In particular, BW, with higher pollution load and less volume amount, should be treated separately before mixing with GW because the pretreatment of wastewater with a high pollution load could achieve a higher treatment efficiency than that with a lower pollution load. For instance, there is a higher organic matter removal rate in the pretreatment of anaerobic reactors for BW with a higher concentration (Singh *et al.* 2019). Moreover, if only the BW, rather than the BW and GW together, in the RDW is pretreated, the volume requirement of the pretreatment equipment could be reduced. The required investment for pretreatment can also be reduced. Additionally, pretreatment of BW could mitigate the wastewater pollution load for end-of-pipe treatment. Eventually, the investment and consumption required for the whole treatment process (consisting of pretreatment and terminal treatment) could be decreased. A source separation-considered management mode of RDW could be more attractive in the future.

Table 4 | Pollutant production coefficients

Household no.	Pollutant production coefficients (g/(cap-d))			
	COD	NH ₄ ⁺ -N	TN	TP
H1 ^a	95.7 ± 48.9	4.7 ± 0.7	5.6 ± 0.9	1.2 ± 0.8
H2 ^a	121.6 ± 71.9	7.1 ± 1.7	8.2 ± 2.6	1.2 ± 0.8
H3 ^a	79.0 ± 48.1	5.6 ± 1.1	4.5 ± 0.7	1.2 ± 0.7
H4 ^a	36.7 ± 18.0	0.5 ± 0.3	0.8 ± 0.4	0.1 ± 0.1
H5 ^a	60.7 ± 26.4	0.9 ± 0.5	1.5 ± 0.5	0.7 ± 0.4
Average ^b	78.7 ± 55.1	3.7 ± 2.8	4.1 ± 3.0	0.8 ± 0.7

^aRow data are the averages and their standard deviations ($n = 15$).

^bRow data are the averages and their standard deviations ($n = 75$).

Pollutant production coefficients of RDW

The pollutant production coefficient is an indicator of pollutant source strength. Previous studies of RDW in Taihu Lake Basin mostly focused on the pollutant concentration in combined household wastewater, and the pollutant production coefficient was not identified, leading to the difficulty in projections of total pollutants. In this detailed source-separated study, the pollutant production coefficient can be calculated. The total generation amount of one pollutant, i.e. the pollutant production coefficient of RDW, can be obtained by combining the pollution loads of the three types of wastewater from one household.

The household was the smallest calculation unit for the generation and discharge of RDW, and the production coefficients of various pollutants was based on data of sample households. The average multi-day value of the five sample households' daily total pollutant generation represents the final pollutant production coefficient. The results are shown in Table 4.

As shown in Table 4, the pollutant production coefficients of COD, NH₄⁺-N, TN, and TP in RDW were 78.7 ± 29.0 g/(cap-d) (range: 36.7–121.6), 3.7 ± 2.6 g/(cap-d) (range: 0.5–7.1), 4.1 ± 2.7 g/(cap-d) (range: 0.8–8.2), and 0.8 ± 0.4 g/(cap-d) (range: 0.1–1.2), respectively. These quantified results, combined with population, can predict the total amount of pollutants of non-point RDW in this research area.

Considering the volume production coefficient (i.e. 94.1 ± 31.6 L/(cap-d)), the synthetic wastewater (consisting of the three types of wastewater) concentrations of COD, NH₄⁺-N, TN, and TP were 836.3 mg/L, 39.6 mg/L, 43.8 mg/L, and 8.9 mg/L, respectively. The concentrations of these pollutants in RDW were all even lower than those

reported in the inflow of UDW treatment plants (COD 1,266 mg/L, $\text{NH}_4^+\text{-N}$ 93, and TP 28 mg/L (Saavedra *et al.* 2019)), indicating that the strength of RDW is relatively lower than the reported UDW. Compared to the concentrations of contaminants in a single BW, the synthetic wastewater concentrations were much lower, which had a negative effect on the wastewater treatment efficiency. For instance, $\text{NH}_4^+\text{-N}$ concentration in BW was 106.3 mg/L, while that in synthetic wastewater was only 39.6 mg/L. It was also found that the pH values of the synthetic wastewater were lower than those of BW. The synthetic wastewater with lower pH value and ammonium ion concentration contained lower free ammonia concentration than BW. The higher free ammonia concentration in BW could kill parasites, while the synthetic wastewater did not have this capacity. That is to say, However, RDW treatment based on source separation can obtain higher efficiency.

The relationship between the pollutant production coefficients, such as the ratio, could be used as a qualitative characteristic of synthetic household wastewater. The COD:TN ratio measured in this study was approximately 19.2, while that reported in the influence of terminal treatment plants was approximately 5 or less (Wang *et al.* 2020). It is recommended to study the pipe network transportation process in the future. According to Table 4, pollutant production coefficients of each sample household varied greatly, indicating that the homogeneity of wastewater from different families was poor. Further investigation with more samples remains to be done. Although studying data from five sample households had some limitations, it provides a feasible source-separated method for investigating the RDW generation characteristics in Taihu Lake Basin, and the referable definite pollutant production coefficient values for the future aquatic environment management in this region.

Suggestions for future RDW management

As shown in Figure 1(c), rural natural villages in Taihu Lake Basin are dispersed. Constructing trans-village sewage collection networks and large-scale treatment plants is not cost-effective for collecting and treating RDW. The installation and maintenance of long-distance drainage networks require significant investment, while large-scale concentrated treatment plants have high operation and maintenance costs (Gao *et al.* 2019a), as well as issues associated with large-scale tailwater reuse with concentrated discharge. Therefore, the centralized management mode is not suitable for RDW. A study on the decentralized

treatment of UDW demonstrated that it was theoretically feasible (Gallagher & Sharvelle 2010) but was difficult to widely implement due to the high density of residential households and shortage of land resources. However, in rural areas of Taihu Lake Basin, natural villages generally consist of dozens of households, and residential households' distribution is concentrated. The decentralized wastewater management mode is more likely to be realized, and the natural village could be taken as the minimum unit. Studies have shown the feasibility and advantages of decentralized treatment of RDW (Ding *et al.* 2019; Hong *et al.* 2019).

Based on the specific rural natural village layout and characteristics of the quantity and quality of RDW, we suggest that RDW treatment should not only adopt the decentralized mode but also source separation, as these could conserve energy and cost and improve pollutant removal efficiency. As stated in this study, natural village houses are independent buildings, which is important in rural residences. Facilities, such as septic tanks, could be constructed in nearby individual households for source separation and pretreatment. According to the rural household layout in this study, domestic wastewater was mainly produced in the kitchen, bathroom, and WC. The sites or links of domestic wastewater production in the rural household are separated. The interior plumbing system in the rural household can provide suitable conditions for source-separated drainage and pretreatment. Additionally, GW is attractive for water reuse from the perspective of quantity characteristics, while BW has potential for nutrient recovery. A source-separated collection system for RDW could keep these possibilities open in the future.

In the last decade, rural households were requested to set up preliminary treatment, such as septic tanks, for pollution retention as a stop-gap measure when there was no alternative for RDW treatment in the research area (Hong *et al.* 2019). If the decentralized management mode of RDW is promoted in the future, a lot of village-level collection networks and terminal treatment facilities will need to be constructed. The connection between the newly constructed facilities and the original facilities is also significant. Source separation and pretreatment could make the most of the numerous pre-built septic tanks, reduce resource waste, reduce cost and achieve better pollutant removal.

In a recent study (Guo *et al.* 2014) into decentralized wastewater treatment technologies and management in rural China, three widely-used modes used in RDW treatment were examined. The difference between these modes

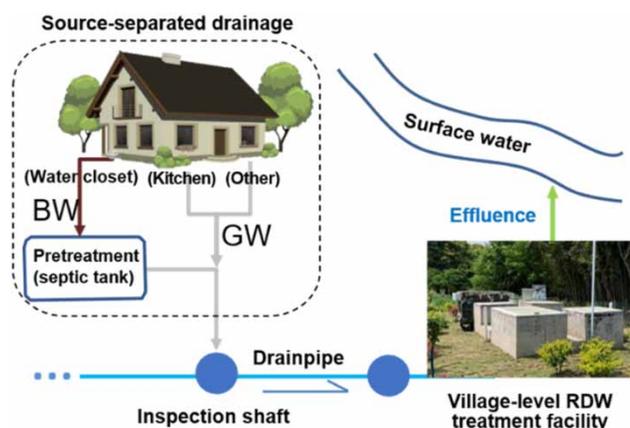


Figure 6 | The village-level RDW management mode with household wastewater source separation.

was only in the terminal treatment process, and the importance of source separation was not mentioned. Considering the generation characteristics of RDW given in this research, source separation should be an important aspect of RDW management, and its value needs to be recognized.

For the reasons mentioned above, the village-level management mode of RDW is suggested, as shown in Figure 6. In this mode, only the wastewater from WC (i.e. BW) enters the septic tank and then the village sewage collection pipeline, while other sewage (i.e. GW) enters directly into the village sewage collection pipeline. Finally, mixed sewage enters the village-level RDW treatment facility where it is processed.

The advantages to this are that (1) pretreatment with source separation could achieve better pollutant and pathogenic microorganism removal performance, especially for BW. For instance, BW and GW mixing would dilute BW around 2–10 times, and anaerobic digestion of separate BW could enhance biochemical methane production (i.e. organic matter removal index) from 30% to 53% under the experimental conditions (Cheng *et al.* 2018). (2) Onsite BW retention and pretreatment could allow future decentralized onsite reuse of BW nutrients in rural areas (Zhou *et al.* 2015). (3) GW, a cost-effective alternative source of water, could still be collected separately if necessary in the future. (4) More than 70 million (Cheng *et al.* 2018) household septic tanks constructed in the China National Toilet Revolution could still be used efficiently instead of being wasted. Overall, a village-level RDW management mode involving household wastewater source separation is promising for rural China in the future.

CONCLUSIONS

In this study, an investigation of the characteristics of RDW with source separation was conducted in a village in Taihu Lake Basin, China. The results showed that the average RDW production coefficient was 94.1 ± 31.6 (range: 71.8–143.0) L/(cap-d). The household RDW generation peaked two or three times daily, and the synchronous fluctuation could cause hydraulic loading shock. The production coefficients of typical pollutants in RDW, including the COD, $\text{NH}_4^+\text{-N}$, TN, and TP, were 78.7 ± 29.0 g/(cap-d) (range: 36.7–121.6), 3.7 ± 2.6 g/(cap-d) (range: 0.5–7.1), 4.1 ± 2.7 g/(cap-d) (range: 0.8–8.2), and 0.8 ± 0.4 g/(cap-d) (range: 0.1–1.2), respectively. Hence, a quantified description of the pollution source strength was given as a reference for RDW pollution prediction and fine management for policymakers. BW from WC sources accounted for 30.4% of the total volume amount and contributed to 93%, 81.7%, and 67.3% of loads of ammonium nitrogen ($\text{NH}_4^+\text{-N}$), total nitrogen (TN), and total phosphorus (TP) in RDW. GW from the kitchen and other sources with low nutrient-related pollutant concentrations and loads, accounting for 69.6% of the total volume amount, was a promising alternative water resource. The characteristics showed the potential of RDW in water and nutrients reuse. The proposed village-level management considering household wastewater source separation is attractive to RDW management to save costs and improve efficiencies.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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