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RESEARCH ARTICLE

# An innovative approach to monitoring non-point source pollution at a field scale: online monitoring system for continuous cropping with a serial pipeline

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## KEYWORDS

Farmland runoff, online monitoring, auto-collection, agriculture, non-point source pollution

## HIGHLIGHTS

- An innovative online monitoring system was developed for non-point source pollution under continuous cropping.
- More precise and lower labor cost automatic monitoring of water quantity and quality was realized in the system.
- This monitoring system could be particularly valuable for the next national pollution source census in China.

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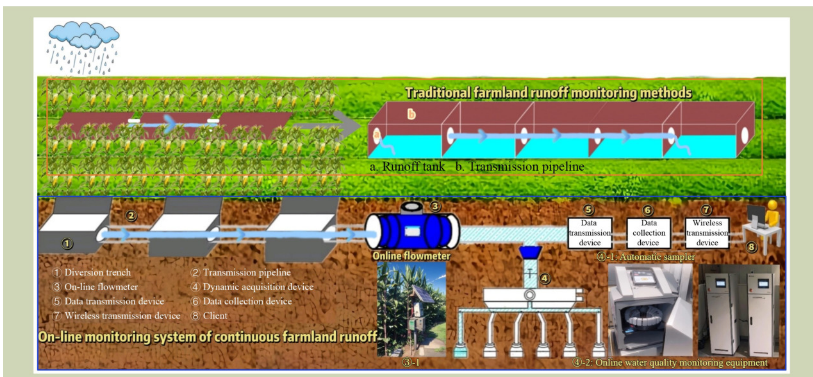
## GRAPHICAL ABSTRACT




## ABSTRACT

Non-point source (NPS) pollution has been the major cause of water quality degradation. However, there are still shortcomings in the current monitoring methods for NPS pollution, such as small monitoring range, error of monitoring data, time-consuming and laborious monitoring process. Although the established method, field experiment plots, was used effectively in the first and second national pollution source census in China. However, when the results obtained by monitoring experimental plots are extrapolated to a field or larger scale, there are considerable uncertainties because of the characteristics of large spatial and temporal variation of farmland. To optimize the farmland surface runoff monitoring methods, an online monitoring system for continuous cropping based on a serial pipeline was developed, which takes diversion trench, online flowmeter and dynamic acquisition device as the main body. Compared with the current farmland monitoring methods, this system can realize more precise automatic monitoring of water quantity and quality, and lower costs. This innovative method will provide greater confidence in the actual monitoring of NPS pollution from farmland and wider practical application. This new method could prove particularly valuable for the next national pollution source census in China.



## 1 Introduction

The agricultural non-point source (NPS) pollution in China is serious, continuing to increase year by year. The results of the first and second national pollution sources survey showed that agricultural NPS pollution has become one of the main causes of water environmental pollution in China[1–3]. Effective prevention and control of agricultural NPS pollution has become an important issue in the field of ecological environment in China. Based on the *Second National Pollution Source Census Bulletin*, the total nitrogen discharge from agricultural sources in 2017 was 1.4149 Mt, and total phosphorus was 212 kt. Of these, the total nitrogen discharge loss from cropping was 719.5 kt, and total phosphorus was 76.2 kt, accounting for 51% and 36% of the total agricultural source water pollutants, respectively[4]. Therefore, cropping is one of the main causes of agricultural NPS pollution[5–7]. Only through the monitoring of NPS pollution in farmland, can the pollution process and composition under different conditions be clarified. Targeted prevention and control strategies of NPS pollution will be formulated. Surface runoff from rainfall is an important contributor to agricultural NPS pollution[8–10]. Therefore, researchers in China and internationally attach great importance to the monitoring of runoff volume and the collection of runoff water samples, which means runoff monitoring and sampling devices are widely used.

The current farmland surface runoff monitoring systems mainly include simulation monitoring, farmland drainage monitoring, runoff field (runoff plot) monitoring[11,12] and runoff pool monitoring[13,14]. Simulated rainfall monitoring is divided into *in-situ* and *ex-situ* simulated rainfall monitoring. Bhandari et al.[15] measured the effects of mulched crops and winter manure application on nutrient loss in simulated rainfall runoff. Liu et al.[16] examined the mechanism of nitrogen and phosphorus loss from farmland on the North China Plain by simulating rainfall in an experimental field. Jing et al.[17] clarified the relative importance of surface runoff and interflow processes to control nitrogen loss under extreme rainfall events by artificially simulating rainfall. *Ex-situ* rainfall simulation monitoring is done by bringing the soil from the study area back to the laboratory to conduct simulated rainfall monitoring. For example, Song et al.[18] used laboratory rainfall simulation to study the effects of different drainage systems on the characteristics of nitrogen runoff loss in slope plots. Wang et al.[19] studied the effects of different surface microrelief treatments on the amount and composition of dissolved organic matter exports during rainfall through rainfall simulation experiments. Ulrich et al.[20], through rainfall simulation experiments, verified that surface runoff was highly correlated with the transport of herbicides to water bodies. Laboratory-based simulated rainfall methods are useful, but the results from laboratory and field experiments would likely be quite different, and the actual conditions in farmland cannot be fully recreated in the laboratory. The runoff plot (or runoff field) monitoring method is the establishment of relatively independent planting plots in farmland, and set up monitoring points in each plot to monitor the loss of runoff, nitrogen and phosphorus[21–23]. However, the integrity of runoff field monitoring is poor; it is not easy to clean and it is difficult to restore the site after heavy rainfall. Based on this, runoff pool monitoring is widely used. Its advantage is that the monitoring area is smaller than the runoff field and it is suitable for farmland on various terrain. Multiple parallel monitoring plots can be established with to provide higher precision results. Although the monitoring of runoff pool is better than that of runoff field, the monitored units are still mostly single plots. It measures the collected amount of runoff water from runoff pool regularly which can easily produce monitoring errors due to errors reading instruments or monitoring delay[24]. In addition, limited to the fixed size of the runoff pool, when the runoff exceeds the volume of the runoff pool, runoff monitoring cannot continue. Therefore, the runoff pool is not suitable for the monitoring of storm runoff process. Also, the existing farmland surface runoff and interflow synchronous monitoring system mainly monitors the surface runoff and interflow of a single field, which is not suitable for monitoring under continuous cropping.

At present, the collection of runoff water samples is divided into manual on-site collection[25–30] and automatic sampler collection[31–33], with the former time and labor intensive. The manual collection is more difficult due to the uncertainty of rainfall and the distance to the monitoring site. However, automatic samplers also have problems. First, continuous sampling of the whole runoff process cannot be achieved, and second, the collected runoff samples cannot represent the overall situation of one-time runoff. As the relevant samplers are only used for single fields, the runoff production of the whole farmland remains unknown. The samplers are inconvenient for the collection of runoff samples at multiple points due to their large size and difficult in relocated them. Therefore, there remains a clear need to better understand runoff processes and the dynamics of pollutants so that control of NPS pollution can be more effective.

Currently, the production and pollutant discharge coefficient method is used for the pollution census of crop production in China. Data from typical units (such as runoff pool) are converted into empirical coefficients, which are then used to estimate the amount of agricultural pollutants entering water bodies. Compared to the first national pollution source census, the second pollution source census made innovations in the method for calculating the discharge of pollutants from crops into water bodies. However, existing monitoring methods still have limitations, including the large scale of the monitoring work and lengthy monitoring times.

In view of these limitations, an online serial pipeline monitoring system for continuous cropping was designed. It has the potential to overcome the problem that the existing monitoring system is not suitable for the monitoring under continuous cropping and rainstorm runoff. It not only monitors the surface runoff under continuous cropping in real time, but also realize the online monitoring at a field scale with automatic real-time sampling.

## 2 Materials and methods

### 2.1 System structure

The online monitoring system for continuous cropping was established downslope. Its main components were a diversion trench, an online flowmeter, a dynamic acquisition device, a data transmission device, a data collection device, a wireless transmission device and a client (Fig. 1).

### 2.2 System principle

#### 2.2.1 Automatic diversion of water samples

The purpose of the diversion trench was mainly to collect runoff and subsurface flow from the monitored farmland and divert them to the transmission pipeline. The diversion device comprised diversion trenches and multiple transmission pipelines. The diversion trenches were connected in series via the transmission pipelines, and the depth of multiple diversion trenches was increased accordingly to ensure water flow. In practical applications, the diversion trench would be a square pool downslope on the side of the adjacent field to collect the runoff.

#### 2.2.2 Automatic monitoring of water quantity

The online flow meters were placed at the end of the diversion device and used for monitoring the runoff flow and subsurface flow under continuous cropping. They were two online flow

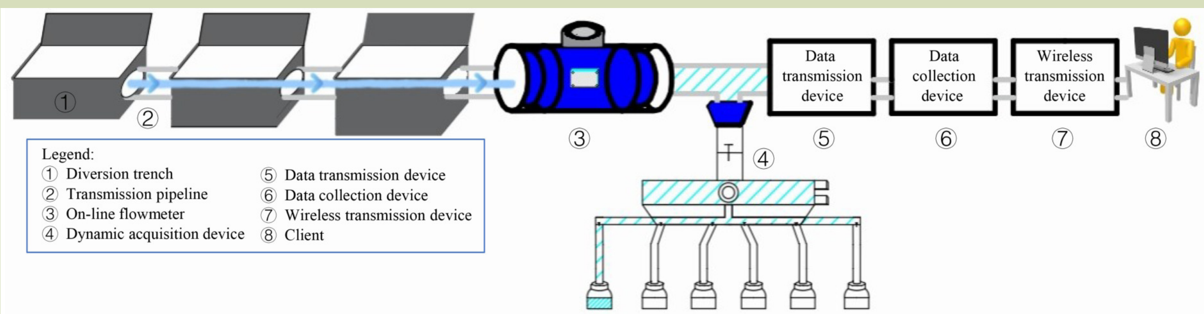



**Fig. 1** Structure of an online monitoring system for continuous cropping with serial pipeline.

meters. The first was positioned at the end of the last runoff transmission pipelines to monitor runoff flow. The second was positioned at the end of the last subsurface flow transmission pipeline to monitor subsurface flow.

#### 2.2.3 Dynamic collection of water samples

The dynamic collection device was placed at the end of the online flowmeter and was connected in series with multiple diversion trenches to collect runoff and subsurface flow under continuous cropping. The device consisted of a rainfall inductor, a segmented valve sensor and multiple sampling bottles with serial numbers. The valve port of the segmented valve was connected to the sampling bottle via a hose. A controller and a timer were components of the segmented valve sensor. The controller was configured to control open and close states of each segment of valve. The timer was used to record the time when the water sample enters the sampling bottle. A liquid level sensors were installed in the sampling bottles to measure the height of the liquid and accurately measure the volume of the liquid in each sampling bottle.

When rain lands on the rainfall sensor a determination is made on whether there is sufficient rain (rainfall > 2 $mm \cdot h^{-1}$) to start monitoring. The flowmeter switch would then be triggered to open a sampling channel. Concurrently, the timer starts until the sampling bottle is full (detected by a liquid level sensor arranged in the sampling bottle). If no water flows into the sampling bottle for more than 2 h, a signal is sent to the controller to automatically shut down the transfer pipeline and the valve. When the next rainfall event occurs, the sample channel and the controller is triggered to collect the runoff water. Similarly, the transfer pipe and the valve are automatically shut down when the sampling bottle is full of samples or no sample flows into the sampling bottle for more than 2 h. The sample in the sampling bottle is recorded as a sample corresponding to the second rainfall. The samples are stored according to the frequency of rainfall, and one sample is collected for each rainfall to realize dynamic collection of farmland surface runoff.

To realize the on-site monitoring of water quality, an online water quality monitoring device was installed after the online flowmeter device. The water quality was analyzed in real time including total nitrogen, nitrate nitrogen, ammonium nitrogen, total phosphorus, dissolved oxygen, COD, pH and conductivity. The installation of an automatic alarm system in water quality monitoring equipment was used to promptly notify the relevant personnel to ensure a rapid response to abnormal water quality.

#### 2.2.4 Data collection and transmission

The data transmission device was used for transmitting the runoff flow and subsurface flow monitored by the data collection device to the client in real time.

## 3 System reliability analysis

### 3.1 Engineering workload

Compared with the current runoff pool, which needs to store runoff, the design of the diversion channel and transmission pipeline of the monitoring system made the design size of the runoff diversion trench smaller. The engineering workload was greatly reduced and the construction cost and time of the project were also reduced. The occupation of land was reduced, and the applicability was higher.

### 3.2 Online monitoring

Compared with the existing farmland runoff monitoring methods, the system was able to monitor the runoff process in real time, both for continuous runoff and intermittent runoff (Fig. 2). Also, the monitoring accuracy was greatly improved (Table 1).

## 4 Applications in the field

### 4.1 Overview of the study area

To further verify the field application performance of the online farmland monitoring system, the *in situ* monitoring point was established in Baizhuang Village, Anzhou Town, Anxin County, Xiong'an New Area, Hebei Province (38.886° N, 115.800° E), the typical area of Baiyangdian Basin (Fig. 3). The monitoring area was flat, 272 m long from north to south and 125 m wide from east to west. The cropping systems was a wheat-maize rotation. The monitoring was mainly of the surface runoff in the farmland area, and the nitrogen and phosphorus concentration in the runoff.

### 4.2 Data analysis

From June to October, during the period of rainfall runoff, the flow and flow velocity of the monitoring points were monitored every 30 min. During the period of extreme rainstorm events, the monitoring frequency was strengthened. On 29 July, affected by the typhoon, there were extreme rainfall

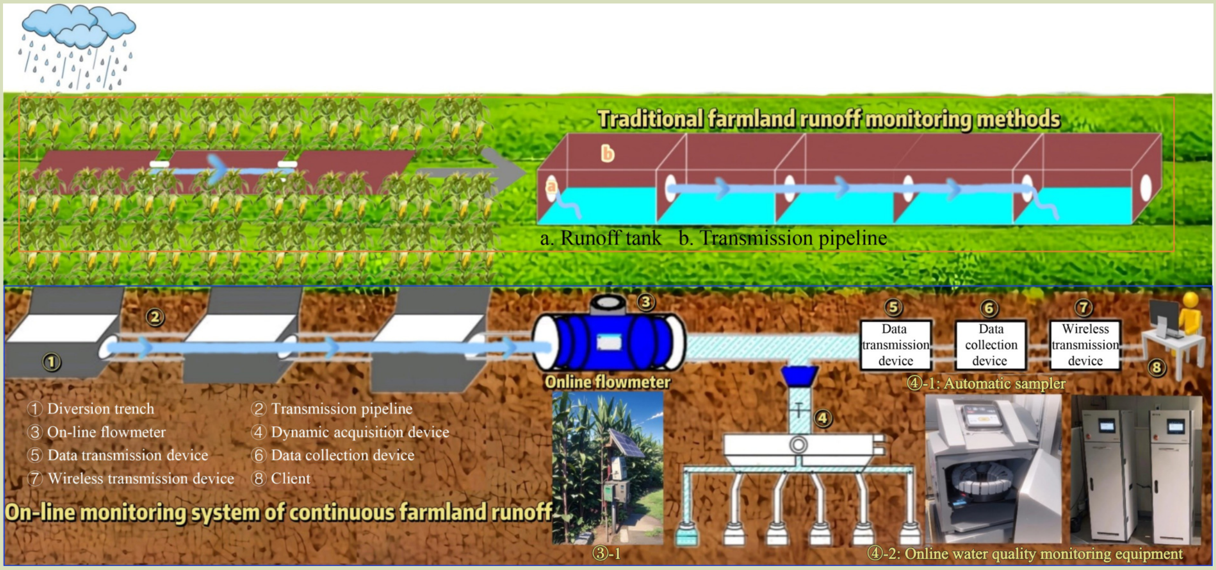



**Fig. 2** Comparison of current monitoring methods and online monitoring system of serial pipeline continuous cropping.

**Table 1 Comparison of current and proposed methods**

| Comparison projects | Concrete parameters | Runoff pool method | Simulated rainfall monitoring | Proposed method |
|---|---|---|---|---|
| Applicable object | a. Runoff plot (several to dozens of square meters) | √ | √ | √ |
| | b. A single field | × | × | √ |
| | c. Farm (contiguous plots) | × | × | √ |
| Monitoring process | a. Single runoff generation | √ | √ | √ |
| | b. Dynamic process of single runoff generation | × | √ | √ |
| Monitoring range | a. Limited range | (√) The range is 0 to the volume of the runoff pool, which is limited by the volume of the pool | √ | √ |
| | b. Infinite range | × | × | √ |
| Monitoring accuracy | a. There is the possibility of error | √ | √ | × |
| | b. High precision, accurate monitoring data | × | × | √ |
| Construction project amount | a. The engineering quantity is smaller, the floor area is smaller | × | × | √ |
| | b. The larger quantities and larger floor area | √ | √ | × |
| Cost of labor | a. Monitoring process automation, without manual | × | × | √ |
| | b. Some manual monitoring is needed | (√) Sampling and testing water samples is time-consuming and laborious | √ | × |
| Degree of authenticity | a. There are differences with the actual planting situation and farming activities | √ | √ | × |
| | b. Completely restore the real planting situation and farming activities | × | × | √ |

events on the North China Plain. This monitoring point was located in the rainfall center, so the rainfall and runoff flow were encrypted and monitored to grasp the runoff flow in real time. The reliability of the device was further confirmed by

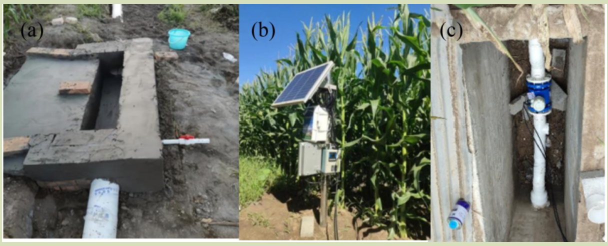



**Fig. 3** (a) Diversion trench, (b) automatic monitoring flow device, and (c) transmission pipeline.

comparing the data obtained from the field with the meteorological data. On 11 August, rainfall occurred again in Baizhuang Village. To understand the changes of farmland runoff after rainfall to better understand the temporal and spatial dynamic characteristics of farmland pollutants with runoff transport, rainfall monitoring was conducted at 30-min intervals at monitoring point. The rainfall began on 11 August and increased on 12 August, but runoff was first detected at 11:00 on 12 August and the flow rate gradually increased (Fig. 4). This indicated that there was a lag in the development of runoff. The reliability of the device was further verified by the field application.

# 5 Discussion

## 5.1 Advantages of the proposed system

### 5.1.1 Conform to the real scene

The main cause of agricultural NPS pollution is agricultural production activities[34,35]. Compared with the current way of runoff monitoring, the monitoring system is installed adjacent to the farmland, which does not affect the agricultural production. It is more consistent in that it captures operational farmland runoff, so that the data are more reliable.

### 5.1.2 Scope of monitoring area

The system can capture farmland runoff quickly and effectively by laying diversion trench and transmission pipelines, and realize the automatic collection of runoff water. Centralized pipeline flow monitoring under continuous cropping (hundreds of hectares) was realized. Compared with the established runoff pool monitoring, it breaks through the limitation that the runoff pool is only suitable for monitoring small fields (tens of square meters).

### 5.1.3 Automation and remote control

By installing an online flowmeter, the runoff and interflow can be monitored online in real time. The acquisition of real-time data are helpful to understand flow dynamics more accurately. Compared with manual monitoring of runoff flow, automated online flowmeters not only provide more accurate and reliable flow data but also set the monitoring frequency arbitrarily according to the actual situation. This is important for timely determination of runoff conditions and making effective decisions. The system supports remote monitoring and control, so that users can monitor and adjust the system through the internet anytime and anywhere, which improves the flexibility and convenience of operation.

The system can automatically collect runoff using dynamic acquisition equipment. Compared with current manual

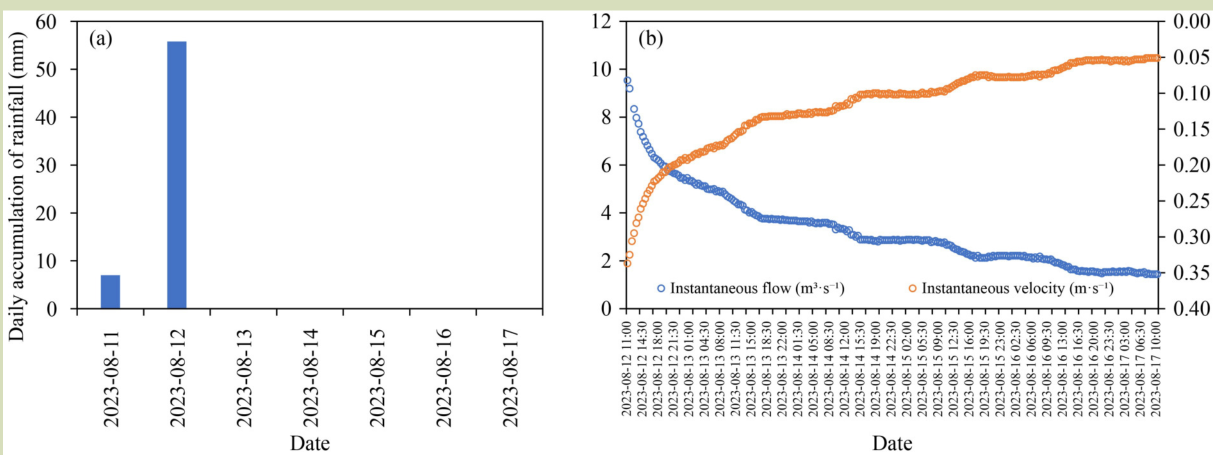



**Fig. 4** Monitoring data in the study area.

sampling, this not only reduces the labor and time cost but also reduces the interference of runoff mixing. Through the installation of online water quality monitoring equipment, water quality can be measured on site. Through the data transmission device, water quality data can be obtained remotely, reducing the cost of sending and measuring samples. Timely monitoring of water quality can reduce the negative impact of farmland runoff on the surrounding environment, help to reduce soil erosion and purify water bodies.

#### 5.1.4 Stability of operation

The operational stability of the innovative method and related devices was greatly improved. First, the device was installed underground, which not only reduced the risk of damage from local farmers during agricultural activities but also minimized the adverse effects of meteorological disasters on the equipment. This is an inherent advantage determined by device design.

Secondly, in 2022, the device was installed in Baizhuang Village, Anzhou Town, Anxin County, Xiong'an New Area, Hebei Province, and has been in operation for 3 years. Additionally, starting on 29 July 2023, the region experienced over 72 h of heavy rainfall. Despite the extreme weather conditions, the device operated normally and continued to transmit data, contributing to the analysis of pollutant discharge characteristics in farmlands during special weather events. The ability of the device to withstand such extreme conditions demonstrates its operational stability (Fig. 5).

### 5.2 Limitations and prospects

#### 5.2.1 Limitations

This method is suitable for plots that require long-term monitoring, allowing researchers to understand runoff and pollutant output from agricultural fields with no need to travel to the site. However, the device is installed without considering the final direction of runoff, so an intelligent valve could be installed at the final confluence of runoff. In the remote analysis of the measured flow data, the opening or closing of the intelligent valve could be controlled to adjust the direction of runoff and protect the surrounding area from flood damage.

**Fig. 5** Monitoring equipment after rain.

#### 5.2.2 Prospect

The current methods applied to experimental plots were useful for the first and second national pollution source census in China. However, when the monitoring results of field experiment plots are used to extrapolate to field-scale NPS pollution, there are considerable uncertainties because of the characteristics of large spatial and temporal variation of farmland NPS pollution. Given to the advantages of the proposed method, it has been selected as the key technology for comprehensive control of NPS pollution by the Chinese Government regulatory authority, the Agricultural Ecology and Resource Protection Station of the Ministry of Agriculture and Rural Affairs[36]. According to needs of specific contexts, relevant units in various places can apply this technology to more effectively study and manage the farmland NPS pollution. Additionally, the proposed novel method could prove particularly useful for the next national pollution source census in China.

## 6 Conclusions

A novel online monitoring system for agricultural surface runoff was developed, featuring a system based on diversion trench, online flowmeters and dynamic acquisition devices. This system resolves the inadequacy of existing agricultural monitoring systems for continuous monitoring and overcomes the uncertainty in data collection, improving the accuracy of runoff monitoring. Additionally, this technology eliminates the need for manual sampling, achieving dynamic collection of agricultural surface runoff and addressing the challenges of online monitoring for field-scale NPS pollution. This system is significant improvement for monitoring agricultural surface runoff and obtaining parameters such as runoff volume, water quality and runoff velocity. It will further aid in understanding the nature and intensity of pollutants discharged with runoff under different conditions, contributing to the management of and substantive reduction in agricultural NPS pollution. This innovative system will help to more accurately assess and manage agricultural NPS pollution, providing effective support for water quality protection and promoting sustainable agricultural and ecological development. Also, the proposed method will likely benefit the next national pollution source census in China.

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**Compliance with ethics guidelines**

Peipei Feng, Gaofei Yin, Qingyi Zhu, Tongyang Li, Bin Xi, Xiaoyuan Xu, Huiqing Jiao, Hongda Wen, Lingling Hua, and Wenchao Li 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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