Remote control rain sampler for rainfall runoff collection

Chengzhi Su, Daiguo Hou, Shiruo Zhao, Xin Li, Zedong Yuan
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ABSTRACT

The availability of high spatial resolutions rainfall runoff data is vitally important in water resource estimation and management. To settle the problem of untimely collection of rainfall runoff caused by the uncertainty of rainfall, an unattended rainfall runoff collector with remote control was developed. According to the whole system, when the trigger device detects rainfall runoff, an energy-saving circuit connects, and the sampler is powered. At the same time, state and position information are sent to the mobile phone through the communication module. Then, the mobile phone sends instructions and starts an order back to the sampler through texts based on different requirements. The instructions and start order are then passed to the single-chip micyoco (SCM) control system, which also occurs via the communication module. A disconnected signal will be sent to the energy-saving circuit after the rainfall runoff collection. This signal will power off the sampler at the end. Test experiments showed that the maximum sampling error of the sampler developed in this paper was 1′02″, and the minimum sampling error was 22″.

Key words | design of rain sampler, rainfall runoff, rainfall uncertainty, remote control

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INTRODUCTION

The availability of high spatial resolutions rainfall runoff data is vitally important for activities in water resource estimation and management (Zheng *et al.* 2015, 2018), especially because it is useful in the construction of 'sponge city' in China (Huan *et al.* 2017). Hence, how to efficiently and accurately collect the amounts of rainfall runoff data has been one of the key questions that needs to be addressed urgently in the area of water resource (Zhang & Zhang 2012; Xie *et al.* 2013). However, it is high cost to collect rainfall sample through ground-fixed densely covered gauges and stations. Generally, it is regarded as an effective method to collect rainfall runoff data by outsourcing with the present rainfall sampler (Akkoyunlu *et al.* 2013). In fact, the equipment timeliness capability limits the implementation of this method because rainfall is uncertain in time and space (Kunde *et al.* 2019).

The current rainfall sampler can be divided into a manual sampler and an automatic sampler. A manual sampler requires field sampling (Galfi *et al.* 2014). Due to rainfall uncertainty, the outsourcing sampling staff must go to different locations and collect samples many times, not only consuming large amounts of manpower and material resources but also exposing them to danger e.g. thunder and lightning, wind and other bad weather (Lentz 2006).

The automatic sampler can automatically start or stop the collection of rainfall runoff samples at a specified time interval and store the collected rain samples in a fixed container, but it cannot start a new collection at any time on a large scale (Bartley *et al.* 2012; Lessels & Bishop 2015, 2020; Automatic Water Sampler MULTI-LIMNOS, Hydro-Bios, Germany). Akkoyunlu and his team (Akkoyunlu *et al.* 2013) developed a sequential sampling

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sampler. They used a detector to perceive rainfall runoff inside the catchment pipe to control the opening and closing of a solenoid valve and, in turn, control whether to start rainwater sampling or not. However, the sensitivity of the detector would be affected by the volume of the rainfall and the uneven distribution of rainfall, and so the sampling moment (from start to finish) is obviously later than the real rainfall moment: the collected water sample is less than the required water sample due to sampling delay. Fang *et al.* (2015) mentioned that their ISCO 6712 samplers collected rainfall runoff samples and adjusted the sampling program according to weather forecast. However, the rainfall forecast is not always accurate in a specific area.

In conclusion, the current sampler achieved automatic sampling to some extent, but real-time sampling is low because the uncertainty of the precipitation still exists, and the sampling period and location of each sample could not be automatically recorded.

To overcome the shortcomings of the above rainfall sampler, an unattended remote-control rainfall-runoff sampler was developed, which can provide an opportunity to collect rainfall with high spatial resolutions through a crowdsourcing manner, and was used by KEBANG TEST on 9 October 2017.

MATERIALS AND METHODS

Hardware description

The principle of the sampler is shown in Figure 1. The composition of the sampler includes a power supply, a single-chip micyoco (SCM) control system, communication module, rainfall trigger device, energy-saving circuit, six solenoid valves and six sampling bottles. The working process is as follows: after the rainfall trigger device detects the rainfall runoff, the energy-saving circuit is connected,

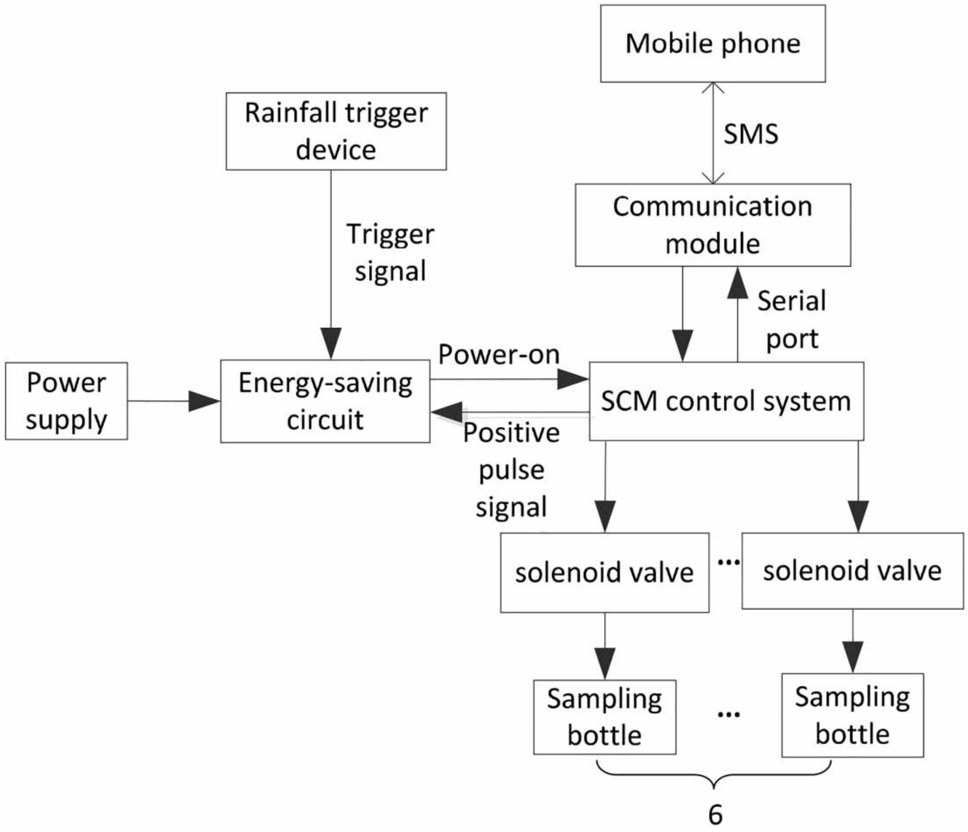

Figure 1 | Working principle diagram.

and the SCM control system and the communication module will be powered on. The communication module receives SCM commands and passes these commands to the SCM control system. After that, the SCM system controls opening of the solenoid valves to start sampling and sends a positive pulse signal to power off the sampler with the energy-saving circuit at the end of sampling.

To detect rainfall runoff in time, the float liquid level control switch was chosen as the trigger device. The trigger device comprises of two float ball switches, one for the reset of the energy-saving circuit and the other for starting the main power. The float liquid level control switch is shown in Figure 2 and works as follows: because the floating ball rises due to liquid buoyancy, the annular magnet is close to the magnetic spring switch. After the magnetic spring switch is contacted, the circuit is turned on as shown in Figure 2(b). Otherwise, the switch is separated and the circuit is disconnected, as shown in Figure 2(a).

The SCM control system is used to receive and process the electrical signals generated by the rainfall trigger device. The SCM control system is composed of IAP15W413S, a crystal oscillator circuit and a reset circuit. It is connected to the communication module through serial ports P3.6, P3.7 and P3.5 and is also connected to the energy-saving circuit through the P3.4 port. The IAP15W413S peripheral circuit diagram is shown in Figure 3①.

The communication module receives the text information formed by the SCM control system and sends this information to the mobile phone so that the sampler can be controlled remotely. The communication module adopts the dual-frequency GSM/GPRS SIM808 module, which detects the SIM card through the interface circuit to cause information interaction with the mobile phone. In addition, the SIM card also acts as the unique credential for sampler identification of multiple samplers. The peripheral circuit diagram of the SIM808 module is shown in Figure 3②.

The purpose of the energy-saving circuit is to reduce the reactive power loss and extend standby time. Without this circuit, the liquid-level float ball may switch the main circuit on and off continuously due to different water levels, especially at the critical position, thereby increasing the power loss. The energy-saving principle of the sampler is as follows: after it receives the trigger signal, the energy-saving circuit starts to power the sampler by connecting the power supply and the sampler begins to work. After the sampling is completed, the SCM control system sends a positive pulse signal to the energy-saving circuit. The energy-saving circuit is disconnected, and the power supply stops supplying the sampler. The energy-saving circuit is constructed of two magnetic holding relays, as shown in Figure 3③. The power supply of the sampler is 1,500 mAh and the nominal voltage is a 3.7 V lithium battery. The sampler consumes 70 mAh of the lithium battery per hour and can work continuously for 19.79 hours. However, after adopting the energy-saving circuit, the sampler consumes a lithium battery capacity of 4.75 mAh per month, and the monthly lithium battery self-discharge amount is 60 mAh. In this case, the standby time of the sampler is approximately 1.65×10^4 hours and is increased by about 834 times compared with no energy-saving circuit.

Software description

As shown in Figure 4, the program execution flow of the sampler is as follows: the sampler remains in standby without the trigger signal. If the rainfall trigger device generates the trigger signal, the energy-saving circuit connects, the

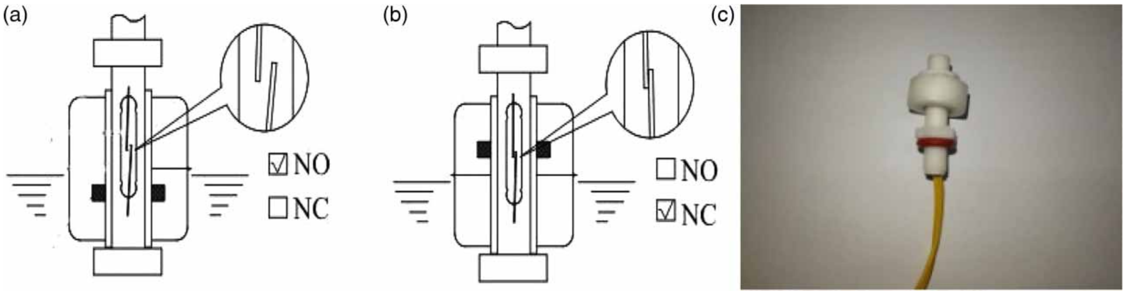

Figure 2 | Float liquid level control switch.

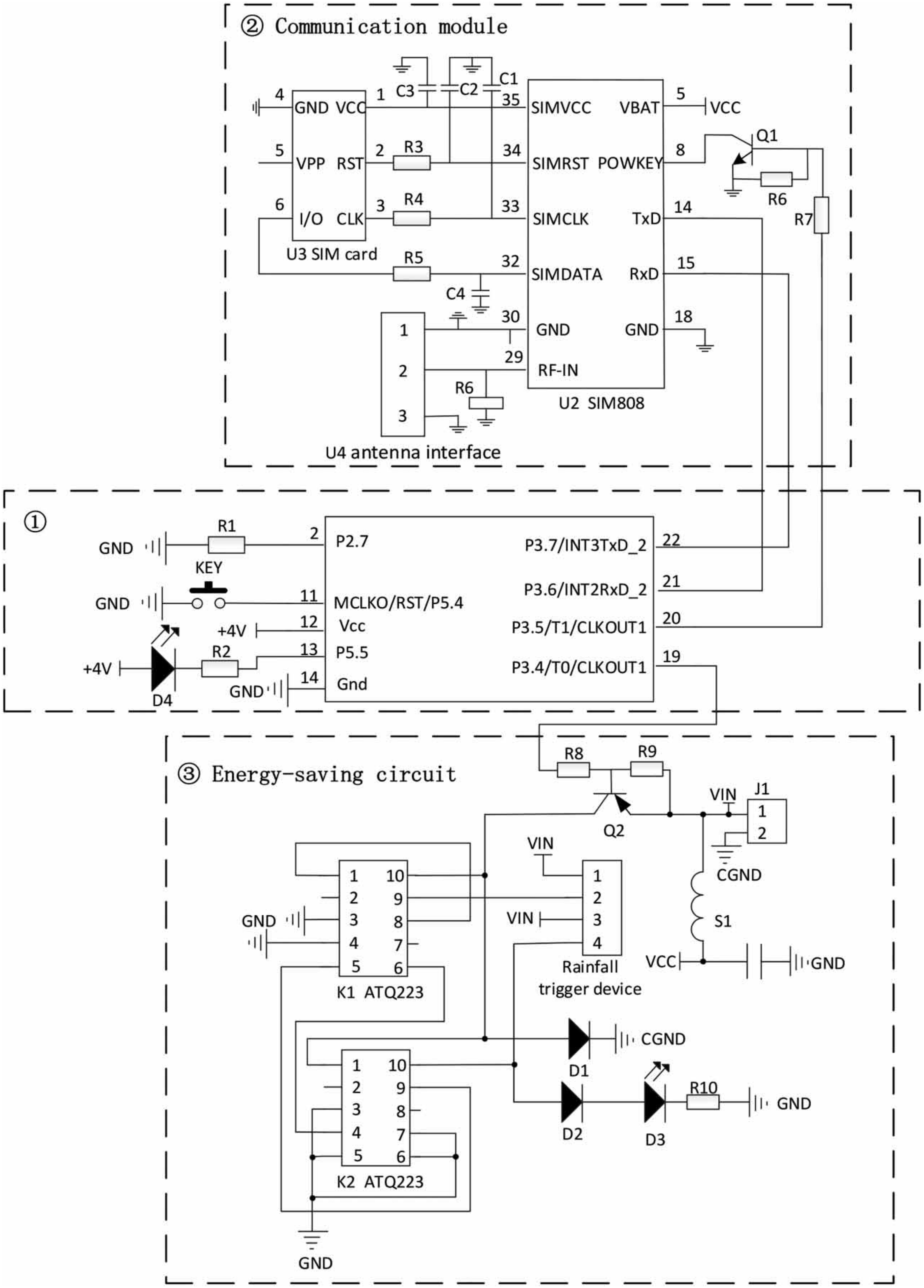

Figure 3 | IAP15W413S peripheral circuit diagram.

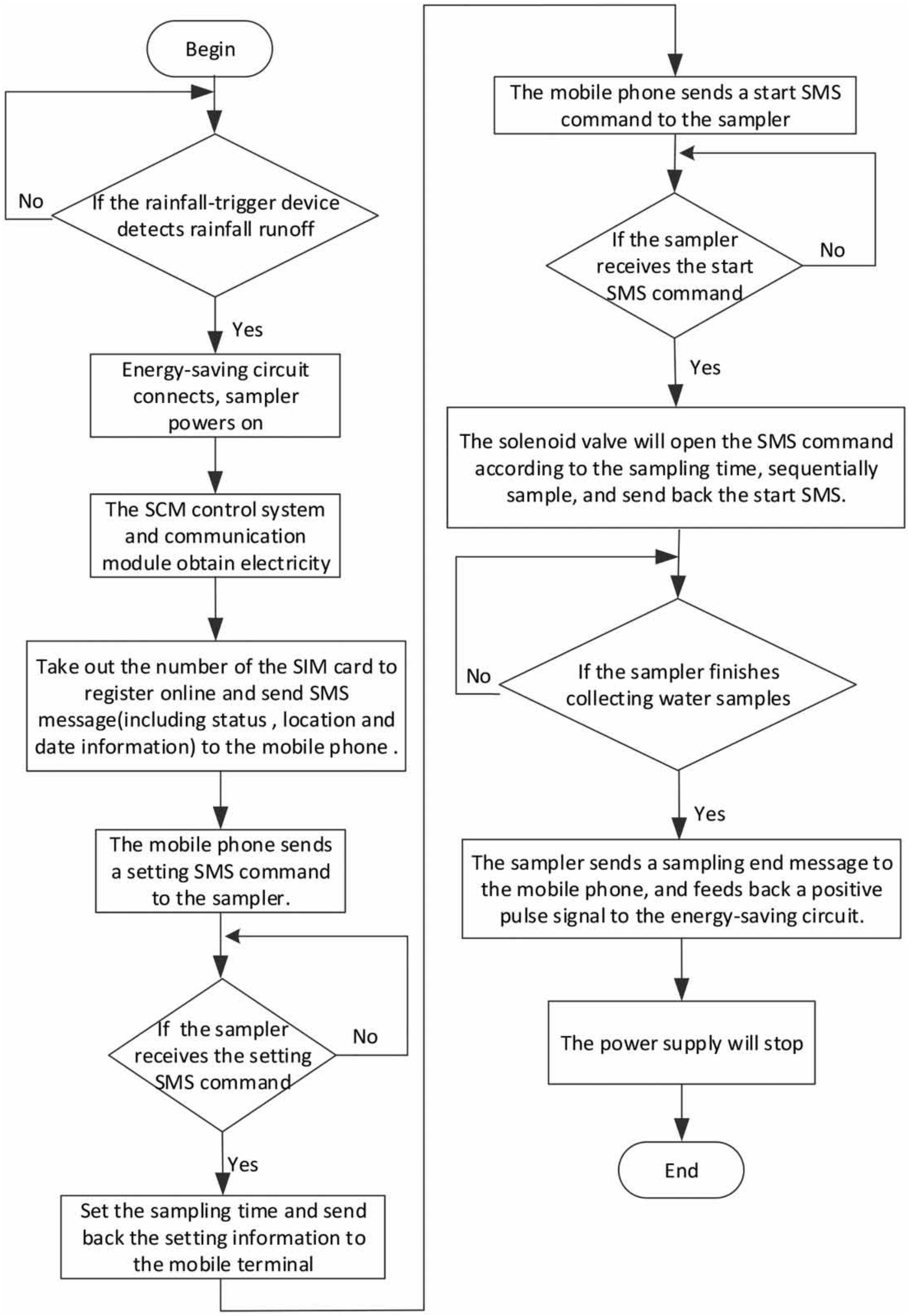

Figure 4 | Program flow chart.

sampler powers on, and the communication module takes out the number of the SIM card to register online and sends the short messaging service (SMS) message (including status, location and date information) to the mobile phone. The mobile phone sends back commands to the specific sampler. The communication module will pass the commands to the SCM control system. When it receives a text indicating that the sampler is ready for rainfall collection, the mobile phone sends a 'start' text to the specific sampler and its solenoid valves are opened to collect rainfall runoff. Otherwise, the sampler will remain on standby. After the sample collection is finished, the communication module will feed back the working situation to the mobile phone and the SCM control system will feed back the positive pulse signal to the energy-saving circuit. The energy-saving circuit will be automatically disconnected after receiving the positive pulse signal and the power supply will stop.

Mechanical description

As shown in Figure 1, the sampler has six solenoid valves and six sampling bottles. During the sampling, six solenoid valves are used as control switches for the six individual sampling bottles to accomplish programmable sequential sampling. Each solenoid valve controls one sampling channel, forming six independent sampling channels, which can effectively avoid secondary pollution of the rain sample during rain sample collection.

The mechanical structure of each independent sampling channel is as follows: the side end of the tee is connected to the water-end outlet of the solenoid valve, forming the inlet channel. The upper end of the tee is connected to the exhaust valve, forming the exhaust channel. The lower end of the tee is connected to one end of the pair of threads. The other end of the pair of threads, through the seal ring and the unthreaded hole of the bottle cap in turn, is connected to the bottle cap with nut threads, and then connects to the tee joint, eventually forming the complete collection channel.

Before sampling, the sampler is placed at the chosen location to ensure the horizontal level of the vent of the exhaust valve is above the inlet level. Since the different liquid level surfaces have different pressures, the pressure of the inlet is greater than the pressure of the gas inside the sampling bottle. When the solenoid valve of the inlet is opened, water flows into the sampling bottle and the air in the sampling bottle will be discharged through the exhaust channel, and so the sampler can collect water without power.

For the sampler to work under water, a waterproof solution is needed. In this paper, epoxy resin pouring sealant was used. The mechanical composition and electronic control composition of the sampler are placed in the mould, as shown in Figure 5(a). The actual sampler is shown in Figure 5(b).

RESULTS AND DISCUSSION

On 9 October 2017 the sampler (as shown in Figure 5(b)) was used by KEBANG TEST for an actual analysis of the collected rainfall runoff samples. Preparation included two

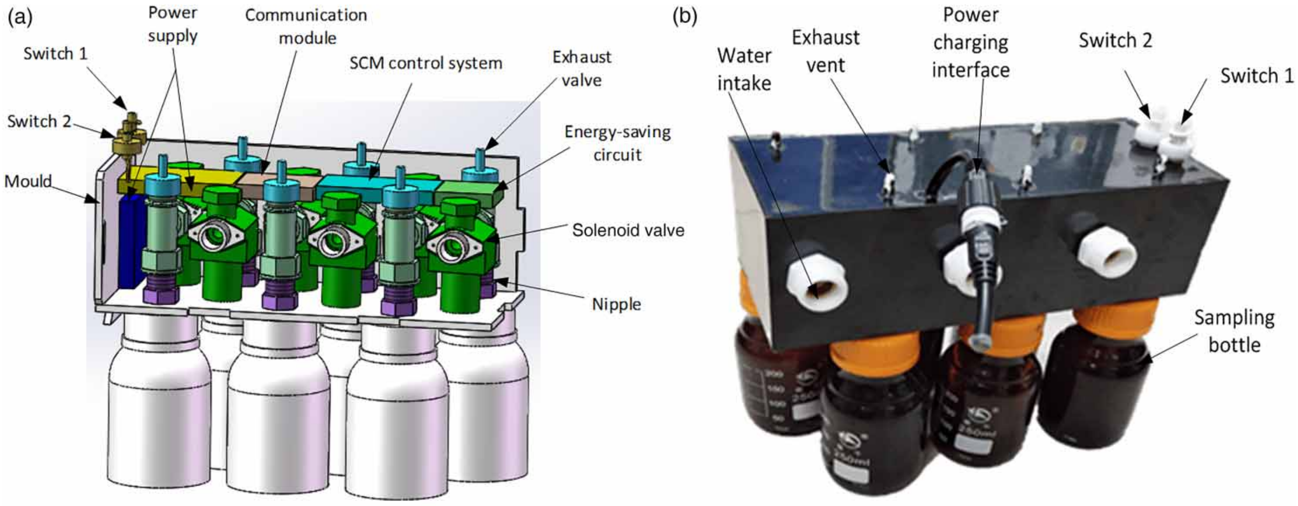

Figure 5 | Placement position diagram and physical diagram.

Table 1 | Location and timetable

Location number	**A**	**B**	**C**	**D**
Latitude and longitude	43.775851, 125.182321	43.776610, 125.175498	43.775184, 125.168610	43.781567, 125.167065
Sampler placement moment	Oct. 9, 2017 AM 08:07:39	Oct. 9, 2017 AM 09:01:21	Oct. 9, 2017 AM 10:37:54	Oct. 9, 2017 AM 13:16:13
Rain moment	Oct. 11, 2017 AM 11:19:36	Oct. 11, 2017 PM 16:40:51	Oct. 15, 2017 AM 02:05:12	Oct. 16, 2017 AM 07:11:08
Sampler starts working moment	Oct. 11, 2017 AM 11:20:38	Oct. 11, 2017 PM 16:41:39	Oct. 15, 2017 AM 02:05:44	Oct. 16, 2017 AM 07:11:30
Sampler ends working moment	Oct. 11, 2017 AM 11:26:38	Oct. 11, 2017 PM 16:47:39	Oct. 15, 2017 AM 02:11:44	Oct. 16, 2017 AM 07:11:30
Sampling error	1′02″	48″	32″	22″

steps: first, the sampler was tested several times in advance to ensure the normal operation; second, 250-ml sample bottles were first washed with distilled water, soaked in 5% nitric acid solution, flushed with distilled water and then dried.

Four locations (marked A, B, C and D, as shown in Table 1) in Changchun in the People's Republic of China were chosen as test sites for the sampler. Since the sampling location is in the wild, it is difficult for the sampling personnel to rush to the designated sampling location for sampling in the rain. According to statistics, the average delay time of manual sampling is 1–2 h. The disadvantages of manual sampling are that the manual effort is labour-intensive, the sampling opportunities are poor and predicting rainfall is difficult. However, the sampler can solve the problem of rainfall uncertainty. Table 1 contains the latitude and longitude of the locations, starting and ending time of sampling and rainfall time. The volume of the sample bottle is 250 ml and, according to the previous test on 9 October 2017, the sample bottle would be full in 3 min. To prevent overflow, the collection time was set at 1 min. From Table 1 we can conclude that the sampling time error of the sampler is 1′02″ to 22″ when collecting water samples. Although the water collector has a sampling time error during sampling, this error is negligible compared with the average sampling time delay associated with manual sampling. The sampler can automatically trigger the collection of rainfall runoff samples, which can effectively solve the problem of the uncertainty of rainfall. Moreover, it can realize the cascade collection of samples and can accurately record the rainfall and rainwater quality in each time period.

The samplers were retrieved once sampling had been completed, and the quality data for four collected rainfall runoff samples are shown as Figure 6. These data are provided by KEBANG TEST and the testing process is in compliance with the Chinese surface water testing standard GB 3838-2002. Conclusions can clearly be drawn from Figure 6, such as the highest pH value was at sampling location A, the least dissolved oxygen (DO) was at location D, the highest chemical oxygen demand (COD) was at location B, and the least total nitrogen (TN) and the highest fluoride ion (F^-) was at location C. The results of the other elements were basically the same.

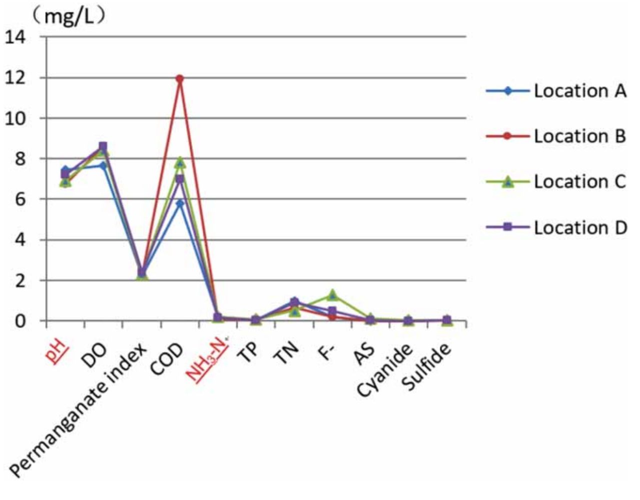

Figure 6 | Test data line chart.

CONCLUSIONS

The remote-control rainfall-runoff sampler can be developed to collect rainfall runoff samples for high-spatial resolution rainfall-runoff data for water resource estimation and management. The results of the experiment indicate the following:

(1) Remote control through SMS instructions solved the uncertainty problem of rainfall runoff collection in time and place (the sampling time error of the sampler is 1′02″ to 22″).
(2) The sampler had six independent sampling channels. Sequential sampling through SMS instruction could avoid secondary pollution during rainfall sample collection.
(3) Immersion sampling utilized different liquid level pressures to complete non-power-driven rain sample collection, which reduced reactive power loss.
(4) With the energy-saving circuit, the standby time of sampler increased to approximately 1.65×10^4 hours compared with no energy-saving circuit.

There are still some deficiencies in this sampler, which can be further improved and studied in the future, concentrating on the following two aspects:

(1) Developing a mobile app for the sampler to allow users to easily check relevant information such as the geographical location and working status of the sampler.
(2) Achieving online detection of rainfall runoff water samples on the existing basis.

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