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Field-Controlled Hydrological Experiments in Red Soil-Covered Areas (South China): A Review

Sanyuan Jiang, Qiande Zhu and Seifeddine Jomaa

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Abstract

Investigation of runoff generation processes and response to changes in catchment characteristics (e.g. land use, soil type, slope, etc.), tillage practice and climate pattern (e.g. rainfall intensity and rainfall duration) is important for understanding of the hydrological cycle and developing land management practices for water and soil conservation. Field and indoor artificial hydrological experiments provide an efficient way for the study of the above processes. This study gave a summary of artificial hydrological experiments using rainfall simulator in China, especially in the red soil-covered region of Jiangxi province. Experiment setting for field and indoor artificial hydrological experiments were introduced; the water balance, runoff components (i.e. surface runoff, subsurface runoff at different depths), runoff amount and relationship to rainfall events were studied and assessment of land coverage and tillage practices on soil and water conservation were conducted. Based on the literature review, it implies that hydrological process at field slope requires more investigation in the following aspects: (1) improvement of monitoring strategies and methodology and isotopic method may be used to improve understanding of hydrological regimes, (2) developing long-term in situ experimental study to analyse soil water movement at different temporal and spatial scales and (3) developing and improving modelling of soil water movement.

Keywords: controlled experiments, runoff processes, water balance, flow pathways, diffuse nutrient losses, soil erosion

1. Introduction

Investigations of rainfall-runoff processes, hydrological flow pathways and water transit time are important for understanding of the hydrological cycle and related nutrient and sediment transport, which may assist developing land management practices with the purpose of water

and soil conservation, prevention of nutrient losses and soil erosion. [1]. Field/pilot rainfall-runoff experiments are traditional and sound approaches to uncover runoff generation processes and assess their responses to changes in topography, land use, soil type, underlying geology and climate patterns. In particular, the artificial rainfall-runoff experiments originated from the 1950s in the USA were conducted for investigation of water and soil conservation and later applied worldwide on research of runoff generation processes and nutrient (nitrogen, phosphorus) losses. Up to now, these approaches are still widely used in investigating nutrient export patterns, the impacts of rainfall pattern (amount, duration and intensity), land use, soil type and antecedent soil water content on nutrient losses [2–4].

Original and reliable data can be obtained from rainfall-runoff experiment and hydrometric monitoring in natural rainfall events. However, it takes long time for conducting rainfall-runoff experiment under natural rainfall condition due to high variability, randomness and uncertainty in rainfall occurrence. It is also heavily impacted by environmental and climatic conditions as rainfall condition cannot be controlled. Therefore, it is difficult to obtain ideal results from runoff generation study under natural rainfall condition and therefore is not efficient. Artificial runoff experiment using rainfall simulator can realise simulation of different rainfall patterns (i.e. combination of different rainfall intensities and different rainfall durations). It can be either conducted in the field or in indoor laboratory by simulating physiographic characteristics and rainfall pattern of the concerned study site. Artificial rainfall simulator can increase the efficiency of the experimental study by overcoming the high randomness in occurrence of diffuse nutrient export and soil erosion under natural rainfall condition [5]. Thus, the artificially rainfall-runoff experiments combined with hydrological and geochemical analysis have become effective techniques for investigation of runoff generation, nutrient losses and soil erosion processes and estimation of pollutants' export loads.

In the following sections, we provide a review on artificial hydrological experiments, with particular focus on those conducted in red soil-covered area in South China, from the perspectives of idea and constructions of artificial experimental facilities, experimental methods (such as hydrometrical methods for various parameters, simulated rainfall equipment, hydrogeochemical methods) and findings obtained from relevant studies. Finally, a summary of challenges in artificial hydrological experiments and outlook of future studies are given. The outcome of this work may provide guidelines for the design and constructions of artificial hydrological experiment based on various objectives, improve understanding of hydrological processes and impacts on nutrient and soil erosion, serve for hydrological modelling development by improving parameter setting and support decision-making on watershed management for water and soil conservation.

2. Design and construction of artificial hydrological experiments
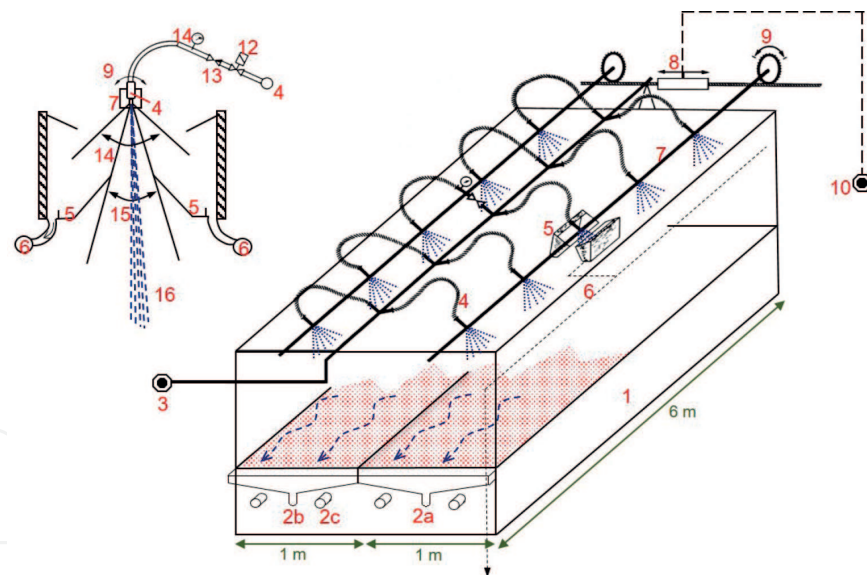
Considering the randomness, uncertainty and difficulties of implementing hydrological experiments and relevant studies under natural rainfall condition, the requests of investigating the spatial variability effect of soil characteristics and rainfall characteristics on runoff generation, nutrient fluxes and soil erosion led to the development of rainfall simulators on small plots.

Iserloh et al. have mentioned that using small rainfall simulators, among others, has more advantages due to the low costs, easy to transport and use in inaccessible areas and low water consumption [6]. This technique has been used worldwide by different research groups where it was beneficial for the investigation of runoff generation processes, assessments of soil erosion by surface runoff and decision-making in soil and water conservation. The design and constructions of artificial (indoor and field) hydrological experiments using rainfall simulator for different purposes are described below.

2.1. Indoor artificial hydrological experiment

Figure 1 shows the schematic design of indoor artificial rainfall-runoff experiment in a flume, which is used to investigate soil erosion processes and influential factors, including rainfall patterns (e.g. rainfall intensity, duration) and soil characteristics (e.g. soil gradation, porosity, precedent soil moisture). An example of such experiment is shown in **Figure 1**.

The erosion flume has the size of 6 m long × 2 m wide. The flume and sprinkling system are described in detail in [7–10]. A summary of the key features is given here. The flume sits on a hydraulic piston so that the slope can be adjusted. The flume can be filled with 0.32 m of a natural soil taken from field site and is underlain by 0.10 m of coarse gravel to facilitate the

Figure 1. Schematic structure of the designed rainfall-runoff soil erosion flume referring to the Ecole Polytechnique Fédérale de Lausanne (EPFL) erosion flume [7, 8]. The slope of the flume can be adjusted within the intervals 0 and 30%. Precipitation is fallen using 10 oscillating sprinkler systems located at 3 m above the soil surface.

excess rainfall drainage. Also, at the downslope end of the flume, there are eight openings collecting the infiltrated water which drains through the soil and gravel. Other four openings (item 2c, **Figure 1**) at the flume's downslope end capture subsurface flow through the topsoil layer. The deep soil and the openings at the bottom and downslope end of the flume allow us to do experiments on unsaturated soils without fully saturating the soil profile during the experiments.

Water is fallen to the flume by 10 VeeJet 80150 nozzles located on an oscillating bar 3 m above the soil surface ensuring the raindrops reached their terminal velocity. The whole flume is divided into two 1-m width identical flumes allowing replicate experiments. Surface runoff is measured as a function of time over the course of the rainfall event for each collector as shown in **Figure 1**. Water from each flume outlet is sampled in individual bottles. Continuous sampling is conducted for the early experiment stage. Afterwards, the sampling time interval increases towards the steady-state equilibrium.

2.2. Field artificial hydrological experiment

It was recognised that the results obtained under carefully controlled laboratory conditions are rarely directly valid in the field due to the high heterogeneity in terms of the influencing parameters on soil hydrological processes. Thus, additional investigations at the natural field conditions are needed.

The eco-science and technology park of Jiangxi province is an ideal field site for researches on runoff generation, nutrient export and soil erosion [11]. It is located in De'an County of Jiujiang City, Jiangxi province with the total area of 0.8 km^2. For runoff generation study, field soil water leakage experiment plot was constructed with a length of 15 m, width of 5 m (horizontal projection) and slope of 14°. The schematic diagram of the rainfall-runoff experimental plot is shown in **Figure 2**. The four sides and bottom of the plot were constructed using reinforced concrete to isolate from surrounding environment; sandy inverted filter was set on the bottom of the plot. Trapezoidal retaining wall was constructed at the toe of the plot using reinforced concrete. In this way a closed draining soil water infiltration device was built. To prevent water entering the plot, the four sides of the plot were constructed using reinforced concrete, which are 30 cm higher than the land surface. After removal of surficial plant and miscellaneous chips, five layers of undisturbed soil were sampled with thickness of each layer 25 cm, and then each layer was stacked. Mean soil density of each layer was measured at the depth of 10 cm, and then the sampled soil was backfilled in the plot to the depth 105 cm in the order of soil sampling with back-filled depth of 10 cm at each time. The weight of backfilled soil was determined using the formula

$$W = V \cdot \gamma \cdot (1 + S) \qquad (1)$$

where V is the volume of backfilled soil at each time (m^3), γ is the dry density of natural soil (kg/m^3) and S is the indoor soil water content (%).
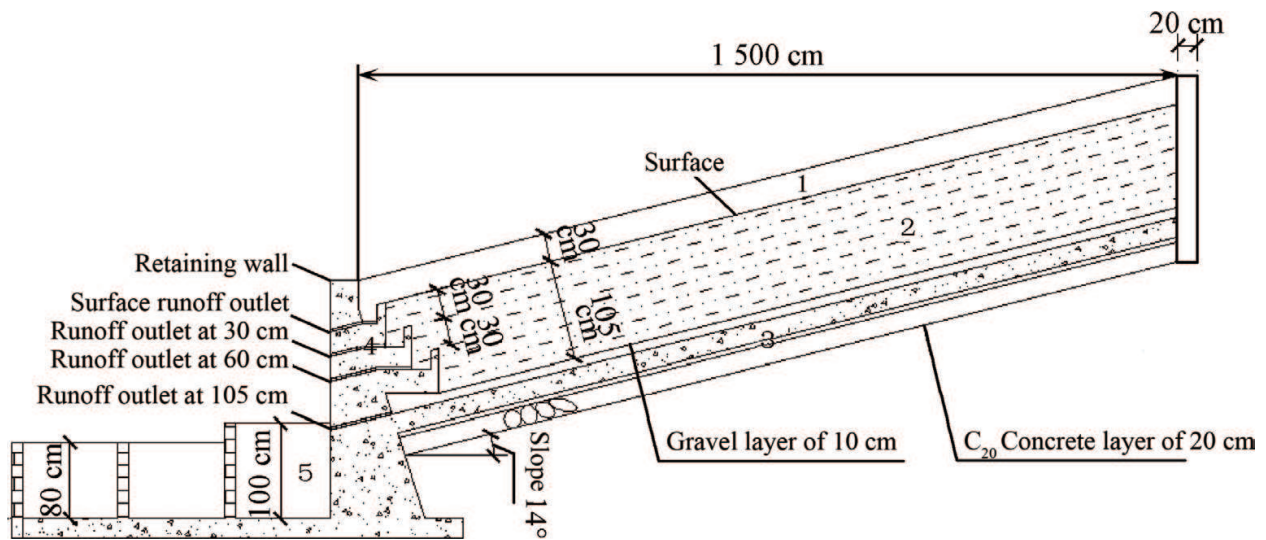
Figure 2. Schematic diagram of the rainfall-runoff experimental plot adapted from [11].

After backfill of soil at each time, soil was compacted to make it achieve the defined depth of 10 cm in order to make the porosity in the backfilled plot similar as that in the natural condition.

In the observation room located at the toe of the plot, four water flow outlets are set from top of the retaining wall to the bottom. The upmost outlet is used for collecting surface runoff and sediment. It connects flow collecting barrel at the bottom of the plot to the surface flow pool via PVC tube. The rest of the three outlets collect underground runoff (i.e. interflow of 30 and 60 cm depth and groundwater runoff at 105 cm below the surface). Horizontal flow collecting barrels were installed in the retaining wall vertically at corresponding depth, which were connected to corresponding runoff pool with bottom area of 1.2 m3. Surface flow pool, interflow pool and groundwater flow pool were equipped with self-record water-level sensor (mode HCJ1) to continuously monitor dynamics of runoff and water leakage generated from different patterns of rainfall events.

3. Artificial hydrological experimental studies

Based on intensive literature review, it is found that artificial hydrological experimental studies can be categorised into the following groups with different objectives: (i) runoff and soil erosion processes and response to rainfall pattern, land use type, slope and tillage approach and (ii) nutrient export and response to land use type, slope and rainfall pattern. Now, a summary of the former studies related to these two perspectives is given.

3.1. Impacts of land use and rainfall on runoff processes

Several parameters are commonly used to describe rainfall-runoff processes, including runoff starting time, share of different runoff components (i.e. surface runoff, interflow at different

layers), water residence time, etc. Wang et al. studied the natural rainfall-interflow processes at different soil layers (up layer of 0–40 cm and down layer of 40–110 cm) under natural rainfall condition in hilly region covered with red soil and found that interflow began earlier and had higher value in oiltea camellia than that in resumed field, while the peak fluxes were oppositional; the response time (i.e. lag) of interflow to rainfall and surface runoff increased with increase of soil depth [12]. Based on runoff plot experiments, Yin et al. investigated runoff at different soil layers with respective depth of 30, 60 and 90 cm to the surface with different types of land cover at red soil field slope in Jiangxi province; results showed that grassland cover increased interflow and prolonged interflow duration compared to bare land. Interflow was positively related to rainfall amount, rainfall intensity, rainfall duration and initial infiltrated rainfall, and runoff was mainly affected by rainfall amount at covered field slope while mainly influenced by rainfall intensity at bare field slope [13]. The effects of Bahia grass and its litter on dynamics of soil moisture and water balance were studied using lysimeter in the field slope covered with red soil, and results indicated that surface runoff of bare land was 24.25 times of that with Bahia grass' coverage and 11.78 times of that with Bahia grass' mulching; the effects of ground cover on soil moisture were different between seasons, and different ground covers could increase or decrease soil moisture [14].

Xie et al. (2014) analysed the characteristics of vertical runoff output in different soil strata on a red soil slope plot under three conditions: vegetation coverage, litter mulch and bare land. The results showed that the total runoff of litter mulch treatment was maximum, followed by the bare land and the vegetation coverage treatment under natural rainfall conditions. Surface runoffs of vegetation coverage and litter mulch treatment were far less than that of the bare land treatment, which were 7.9 and 9.8% of the bare land, respectively. The planted grass and the litter mulch can reduce surface runoff significantly. Interflow of the bare land treatment was the least, which was, respectively, 56.4% of the vegetation coverage and 35.6% of the litter mulch treatments. It demonstrated that both vegetation and litter can increase water seepage. Underground runoff was the main way of runoff output on red soil slope under different treatments, and interflow and surface runoff were directly related to the presence or absence of ground coverage. All different runoff components showed seasonal variation characterized by high runoff in spring and summer, whereas lower runoff in autumn and winter due to temporal change in precipitation [11]. In most studies on groundwater runoff at field slope, the sum of interflow and groundwater flow was considered as a whole without division. In forest watershed, runoff was found to be dominated by groundwater runoff (may be above 39% of the total runoff), while surface runoff had small share (around 1–8% of total runoff) [15, 16].

Xie et al. [2010 b] assessed the effect of runoff reduction through different forest vegetation measures for soil and water conservation in hilly-land area of Jiangxi province using sample-plot and runoff-plot methods; results showed that the interception amount by forest canopy followed the descending order of Pinus elliotii, Masson pine, neddle-broad leaf mixed forest and Chinese chestnut, while the effective interception amount for litter and water holding of soil followed the descending order of Chinese chestnut, neddle-broad leaf mixed forest, Masson pine and Pinus elliotii; the rate of runoff reduction through multilayer vegetation measures was above 90% [28]. Based on statistical analysis on runoff plot experiment in red soil area, Xie et al. [17, 18] found that it was an effective approach to raise the level of vegetation

structure and vegetation coverage supplemented with necessary engineering measures for soil and water conservation in slope land of red soil in South China.

Xu et al. investigated the characteristics of interflow in the purple soil of field slope under different rainfall intensities and land surface conditions and found that the runoff coefficient and average interflow on undisturbed abandoned lands are 3–15 times and 7–33 times that of bare-cultivated lands, respectively; the difference in runoff generation becomes more evident with increase of rainfall intensity [19]. By the setup through a flow collection system, Liu et al. investigated runoff generation process and found that under condition of small rain, surface runoff and the lag to the flow peak might occur if the soil was dry before the rainfall and surface runoff were primarily controlled by infiltration-excess runoff mechanism [20]. Using rainfall simulation experiments, Zhao et al. assessed different pastures' runoff features under different rainfall intensities, antecedent moisture contents and slope gradients; results showed that ryegrass performs better in delaying time to runoff and reducing runoff coefficient, rainfall intensity and antecedent moisture content as well as gradient that affect runoff features [21].

3.2. Impacts of slope and tillage on runoff processes

Xie et al. studied the effects of tillage measures, such as down-slope tillage, cross-slope tillage and weed clearing in garden on soil and water conservation using field standard runoff plot method and 5 years' monitored data. Results showed that the order of the test plots from superior to inferior in reducing runoff and sediment loss was cross-slope tillage plot (75.33% and 80.57%), down-slope tillage plot (59.56% and 65.11%), weed clearing plot (21.73% and 38.08%) [22]; the runoff from April to September was more than 85% of the annual total runoff, and the sediment loss was more than 90% of the annual sediment loss; interplanting to increase field covering is an effective measure to prevent water loss and soil erosion, and cross-slope tillage is superior to down-slope tillage [27]. In field slope, Huang investigated the impact of different grass-growing methods on soil erosion and found that no matter which method is used, it can effectively decrease surface runoff and soil losses in comparison to bare pure agricultural land [23]. The reduction impact of land coverage and cultivation methods on runoff generation and sediment load as well as flow velocity by grass coverage in orchard were also reported in many other studies through field slope studies and in situ monitoring [24–26]. Xu et al. assessed the impacts of cultivation method, soil thickness, slope and rainfall intensity on interflow at the region covered with purple soil using artificial rainfall-runoff experiment and found that there was a lag between interflow and surface runoff; runoff generation showed single-modal process with slow variation [27]. Based on automatic monitoring of soil moisture, water potentials and runoff on a typical sloping farmland covered with purple soil, Lv [2013] found that the soils on different sections of sloping farmlands had differential water storage ability, following the order: upslope<middle slope<down slope; with the increase of depth, the water content showed less evident change; rainfall characteristics and soil heterogeneity affected soil water content change and soil water movement pattern; deep subsurface flow of a typical rainfall event showed obvious delay between rainfall and runoff; rainfall events of different intensity had different subsurface runoff coefficient (subsurface runoff coefficient was 53.6% to the large

rainfall event while the coefficient was only 1.6% to the small rainfall event); the anteced-ent soil moisture content also significantly affected the runoff coefficient in the vadose zone [20]. In artificially field slope rainfall-runoff experiment, Ding found that under the same rainfall intensity, the share of interflow in the total precipitation increased with rise of runoff plot's slope, while the percentage of the subsurface flow occupying the total precipitation increased with the decrease of rainfall intensity under the same slope gradient [29]. Wang et al. [2017] investigated the effects of tillage practices and slope on runoff and erosion under simulated rainfall in laboratory plots and found that AD (Artificial Digging), AH (Contour Plow) and CP (Contour Plow) can be adopted as a beneficial summer tillage practice for controlling erosion during summer fallow period because it delayed the time to runoff, decreased runoff and sediment, increased infiltration, which in turn promoted rainfall water and soil conservation [30, 31].

4. Conclusions and outlooks

This study gave a summary of controlled hydrological experiments using rainfall simulator in China, especially in the red soil-covered region of Jiangxi province, including the design and construction of artificial hydrological experiments, studies and outcomes related to the impacts of slope, land use, tillage, rainfall patterns and antecedent soil moisture on runoff generation and sediment export. Results showed that grass covered slope arable land had lower surface runoff and sediment fluxes, higher subsurface runoff, peak flow, and tailing time relative to bare land; the response of subsurface flow was faster to rainfall and surface runoff from lower to upper layer and lag time increased with increasing soil depth; sub-surface runoff had close relationship with rainfall amount, rainfall intensity affected peak subsurface runoff substantially, but did not impact starting time and runoff of subsurface flow; rainfall pattern affected subsurface runoff generation considerably including hydro-graphs and runoff; precedent soil water content had direct influences on runoff generation and runoff of subsurface flow, characterized by decrease of lag time, increase of runoff and peak flow with increase of precedent soil water content. Runoff plot test is a principal method for research of soil and water conservation and also the main approach of runoff sedimenta-tion measurement. The design of runoff plot should obey the principles of improving the accuracy and decreasing the error of tests, saving construction materials and cutting down project costs, reducing the difficulty of construction and enhancing construction quality, as well as being conducive to post observations and lessening operating costs [31]. Although many studies have been conducted worldwide on soil water movement and transformation on field slopes, most of the former researches were focused on surficial soil water movement in indoor artificial rainfall condition with homogeneous initial soil water content and field slope. Some similar studies have been conducted in the field, however, the studies on infil-tration of soil water during rainfall period and its redistribution after the infiltration are not sufficient; most studies do not relate rainfall-infiltration, runoff generation at field slopes, and soil water dynamics; spatial heterogeneity of soil property, hysteresis, surface crust, plant interception, and water uptake by roots were not comprehensively considered. In particular, studies on redistribution and export of surface runoff, interflow and groundwater flow are lacking [32].

In the future, hydrological process at field slope requires more investigation from the following perspectives: (1) improvement of monitoring strategies and methodology. Isotopic method provides an efficient way to reveal hydrological process at field slope, which may improve understanding of hydrological regimes; (2) artificial hydrological experiments may contain certain extent of uncertainty during to heterogeneity in rainfall and physiogeographic condition (e.g. soil type, dryness, porosity), design and installation of long-term in situ experimental study to capture variability of soil water movement at different temporal and spatial scales and (3) development and improvement of modelling tool for simulation and prediction of soil water movement under different climatic condition and catchment characteristics, which may assist watershed management for water and soil conservation.

Acknowledgements

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