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Practice on the Watershed Hydrological Experimental System Reconciling Deterministic and Stochastic Subjects Based on the System Complexity: 2. Practice and Test

Jiu-Fu Liu, Ai-Min Liao, Niu Wang, Jin Lin, Hong-Wei Liu, Wen-Zhong Wang, Tao Ma, Zhao Cai, Min-Han Liao, Xue-Gang Li, Peng Zhuo, Na Yang, Jia-Ju Lu and Wei-Zu Gu

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Abstract

This is the second of a two-part series on the watershed hydrological experimental system (WHES) aimed at practice and test of it at Chuzhou Hydrology Laboratory. It constitutes both natural and artificial entities of different scales, within which two typical main subjects are reviewed here. First is a natural watershed Nandadish, which is subjected to be a Critical Zone Experimental Block, under manipulation strategy of constrain complexity to compare with the pure natural watersheds, it is the controlled-natural as we termed. Second is an artificial catchment Hydrohill, under the strategy of add complexity to compare with the simple artificial lysimeters, it is the artificial-natural as we termed. The constructions and instrumentations of these experimental catchments are reviewed, especially their renovation version during recent years after a long abandonment. Some results get during the operation of Chuzhou WHES are outlined here as well.

Keywords: watershed hydrology, hydrological experimentation, critical zone experimental block, artificial catchment, controlled catchment, Hydrohill

1. Introduction

A framework of watershed hydrological experimental system (WHES) is suggested raised from the theoretical study on the complex hydrological system. It is defined as an experimental system to dialog with the complex watershed hydrological nature, to drive the opening of various doors of their black boxes aimed at revealing mechanisms hidden deep in the system with some degree of organization. In fact, the organization of the WHES is trying to reconciling the deterministic and stochastic extremes for the watershed hydrological complex system, “opposites are complementary” as the basic Chinese philosophy have revealed.

As a trial of the suggested WHES, the Chuzhou WHES is ongoing for tests. The constituent parts of the WHES can be resolved into four categories as the “macros”, “mesos”, “micros,” and the “nucleus”. “Macros” are composed by pure natural EBs at high level of complexity and randomness; “micros” by pure artificial chain at low level; they are two extreme levels in WHES, while the “mesos” are the chain of intermediate phase; actually, it will play the critical role, the “golden mean,” in WHES as described in Chapter 11. The “nucleus” are water isotopes and solute isotopes from all chains of macros, mesos, and micros by overall sampling; it characterizes the internal linkages between them, and reveals their interrelated processes; actually, it is an essential condition of in WHES.

In Chuzhou WHES, there are two extremes in the intermediate “meso” blocks (Figure 8a in Chapter 11): One is the controlled-natural Nandadish based on the strategy of constrain complexity, another one is the artificial-natural Hydrohill on that of add complexity. Nandadish is designed to meet with the idea on Critical Zone Experimental Block with an intention trying to replace the current Experimental basins suggested by the Representative and Experimental Basin Programme of the first International Hydrology Decade (IHD) since 1965. These two typical experimental meso-mediation blocks of Chuzhou WHES are reviewed here.

2. Practice on the WHES: I–Nandadish, a natural CZEB

2.1. The constructions of Nandadish

Nandadish catchment is a forest watershed with a surficial drainage area of 7897 m². Before its setting, a geological exploring was made by using of 69 drillings distributed in an area covering not only the surficial watershed drainage area from its surficial divides but more area outside. The bedrock elevation of every drill was then measured, so the hypsographic map of the bedrock can be made, together with that of ground surface, the isopachous map of its Quaternary deposit can then be get as well (**Figure 1**). Also from eight drillings with depth penetrating through the bedrock with core sampling for the formation and lithology explorations, no fault, no fracture, and obvious fissures were found from this igneous stratum of andesitic and tuffaceous facies with a thin-weathered layer. It is good for our idea of *controlled-nature*. The depths of its quaternary regolith resting on the bedrock have a range of 1–7 m with an average of 2.46 m (**Figure 1**). It is deeper near the upper divide but only ca 1 m in thickness near the outlet, making the catchment easy to close via a concrete wall installed to the bedrock at the outlet. The vadose zone consists of brunisolic soil of heavy loam, medium

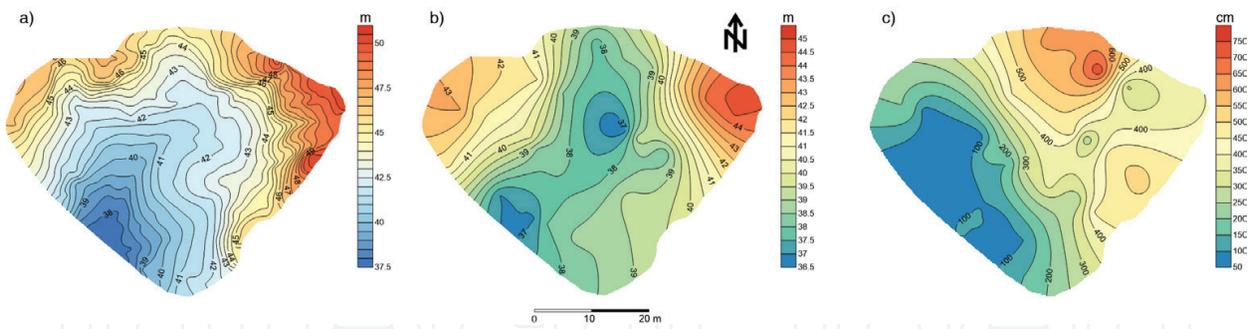


Figure 1. (a) Hypsographic map of the ground surface of Nandadish; (b) hypsographic map of the bedrock surface; and (c) Isopachous map of the deposit thickness (including surficial soil).

and clay loams; saprolite with prismatic and block structures, horizontal and vertical fissures and cracks developed in the upper regolith. The altitude difference of watershed approaches 12.9 m with a surface slope ranging from 6.7 to 17.1%.

Aimed at a CZ hydrological experimental block aforementioned, the main construction tasks as sketchily shown in **Figure 2a** are threefold: (1) To change its original trench into the layered

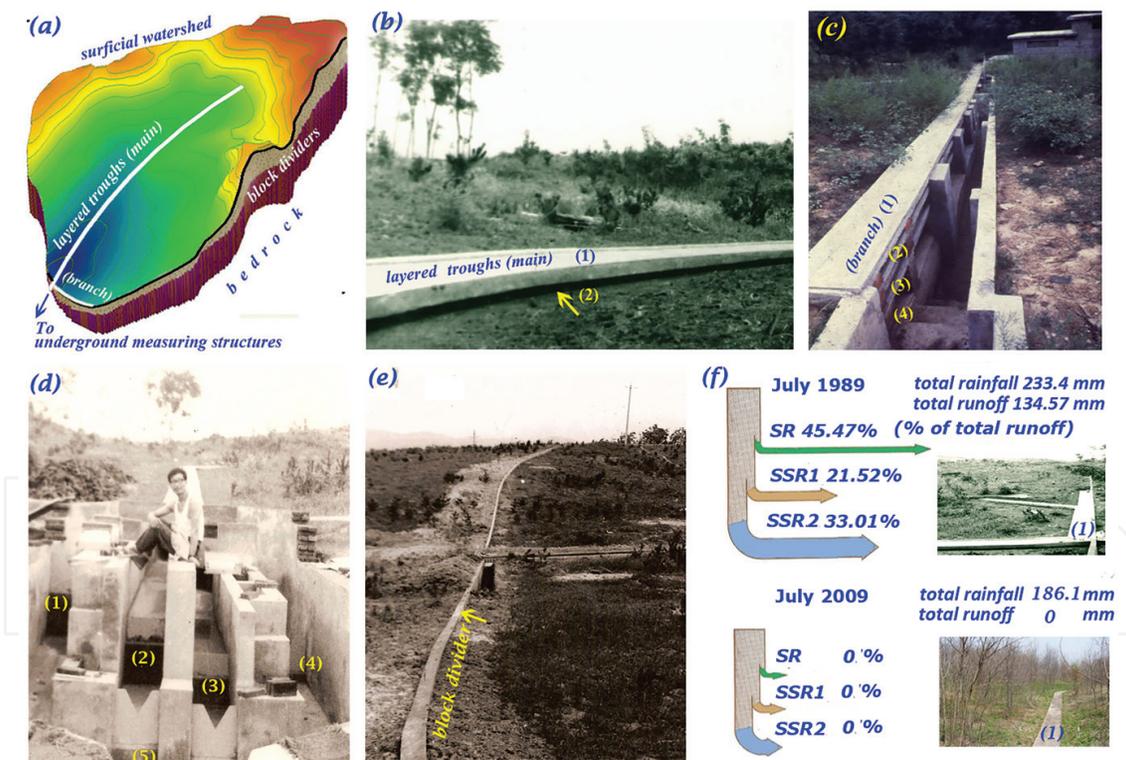


Figure 2. (a) Schematic diagram of Nandadish showing the locations of main construction tasks; (b) original view of the main troughs and the catchment coverages during 1980; 1-trough for rainfall, which is served for separation of “channel rainfall” from surface runoff collected from trough 2, 2-for surface runoff (SR); (c) original view of the branch troughs with a watching gallery for the students practice to seeing the real processes of different runoff components during rainfall event; 1-trough for rainfall, 2-for surface runoff (SR), 3, 4-for subsurface runoff (SSR) from troughs at different depths; (d) measuring structures under construction for different troughs, 1-for rainfall (V-notch sharp crested weir), 2-for SR (V weir and rectangular sharp crested weir), 3-for SSR (V weir and rectangular weir), 4-for SSR (V weir), 5-for total runoff (V weir and rectangular weir, not shown); (e) a part of the underground “block divider” with 0.3 m above the ground surface; (f) the change of runoff compositions within time span of 20 years compared with July 1989 and July 2009 using same measuring structures with different catchment coverages.

trenches aimed at collecting different runoff components for direct monitoring and sampling as well. From the natural surficial topography, a main trench and a branch trench are set up both with four layered troughs with locations shown in **Figure 2a**, the general view is shown in **Figure 2b** and **c**; (2) These troughs are led to discharge measuring structures separately within an underground building, the original view of four measuring structures under construction corresponding to troughs, respectively is shown in **Figure 2d**; (3) For setting of a *controlled-natural* entity, it needs to close all the underground surroundings until bedrock, the “block divider”, aimed at *constrain complexity* aforementioned as shown in **Figure 2a** and **e**, it is 367 m in total with average depth of 2.94 m from bed rock to 0.3 m above the ground surface. It is only completed partly because of seeking for a better engineering method for the limited working space.

The coverage during the watershed’s construction in 1979 was natural grasses with small shrubs and a few Masson pines aged 5–6 years (**Figure 2b** and **f**). Since then, coverage has shifted to a dense forest with canopy height ca 12 m. There are two dominant tree species (*Q. acutissima* Carruth and *B. papyrifera*) accounting for ~90 and 10%, respectively. The new version of that forest watershed is shown in **Figure 3**.

It follows that a hydrological change is happened, which is summarized in **Figure 2f**, compared with the total runoff 134.57 mm of July 1989 with monthly rainfall of 233.4 mm, the total runoff and all runoff components including surface runoff and subsurface runoff of July 2009 are zero all and even having less monthly rainfall of 186.1 mm. So, the setting of troughs during the renovation of CHL is considered and will be described in the following paragraphs.

2.2. The instrumentation of Nandadish

2.2.1. Precipitation

The redistribution of rainfall intensity by the canopy is one of the main research topics in Chuzhou Hydrology Laboratory. Rainfall observation system (**Figure 4a**) in Nandadish was



Figure 3. The bird’s eye view of the forested Nandadish watershed taken at May 2018. 1-trench with layered troughs; 2-block divider; 3-house for discharge measuring structures.

built up to observe rainfall over trees, rainfall under trees (i.e., throughfall), and stem flow to determine the temporal and spatial redistribution of rainfall, and to estimate the canopy interception. To observe rainfall over trees, four tipping bucket rain gauges were mounted on towers located on the four directions and center of the catchment (**Figure 4b**). To observe throughfall, 8 tipping bucket rain gauges, 80 micro rain gauges under trees, and 94 standard rain gauges under trees were installed under trees (**Figure 4a** and **c**). Stem flow was collected in 14 trees from two dominant tree species (*Q. acutissima* Carruth and *B. papyrifera*) using stem flow collection collars and tipping bucket flow meters (**Figure 4d** and **e**).

To accurately determine the ratios of throughfall, stem flow and canopy interception to gross rainfall, a large quadrat with an area of 25×25 m (**Figure 4f**) and a rainfall station under trees with an area of 8.45×4.05 m (**Figure 4g**) were constructed in the Nandadish. In this rainfall

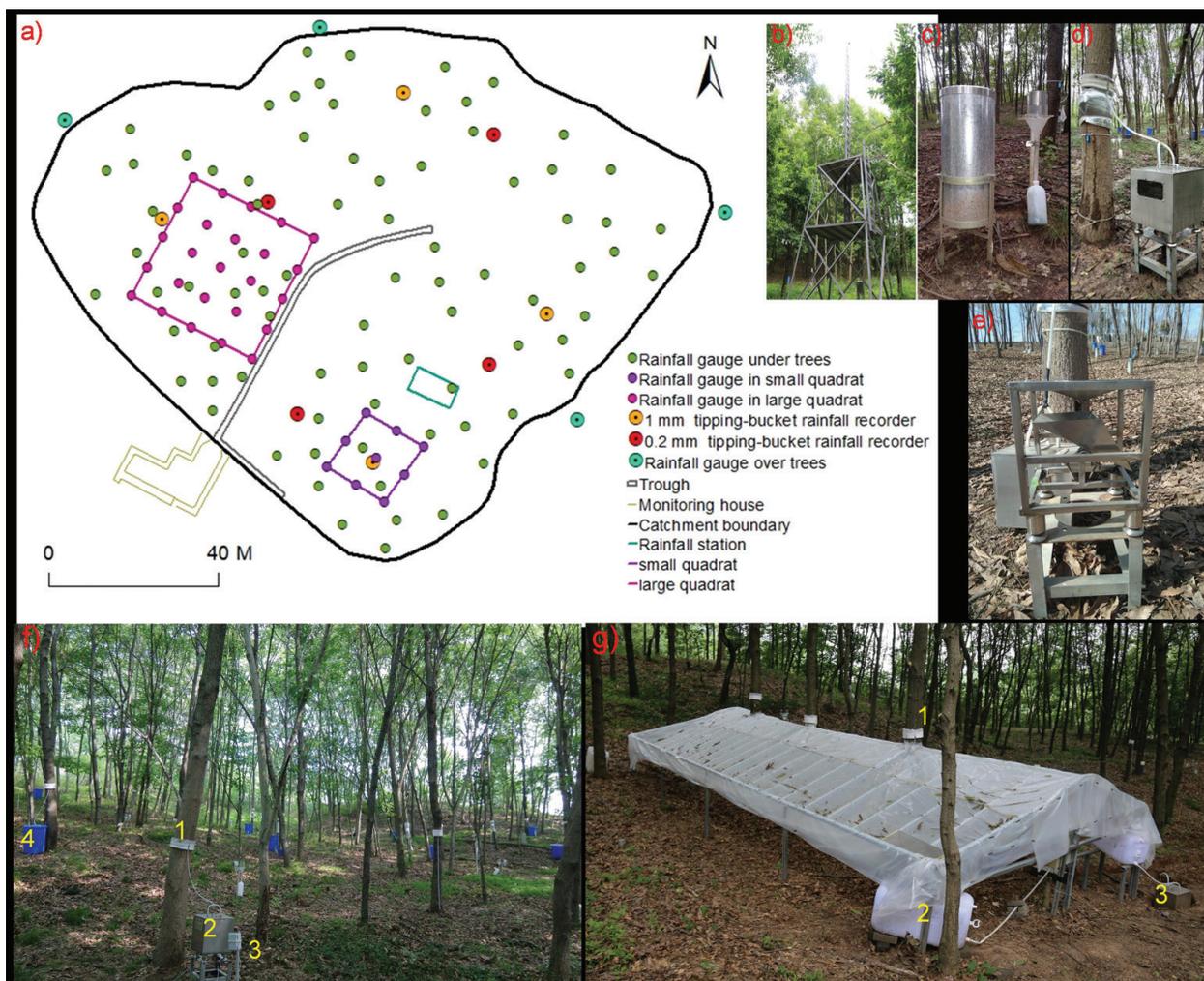


Figure 4. Instrumentation for precipitation measurement in the Nandadish: (a) locations of stainless troughs and rain gauges; (b) four tipping-bucket rain gauges were mounted on towers; (c) micro rain gauges and standard rain gauges under trees; (d) stem flow measurement using collection collars and tipping-bucket flow meters; (e) the inner construe of the tipping bucket flow meter; (f) photograph of a large quadrat with an area of 20×20 m (1-the collection collar collecting stem flow, 2-a tipping-bucket flow meter with 500-mL buckets used to determine the stem flow process; 3-a 100-L water container used to measure the total amount of stem flow); (g) a rainfall station under trees with an area of 8.45×4.05 m (1-the collection collar collecting stem flow, 2-a 150-L water container used to buffer the throughfall flow so that the following tipping-bucket flow meter is capable of measuring the flow when strong rain occurs, 3-a tipping-bucket flow meter with 2.0-L buckets).

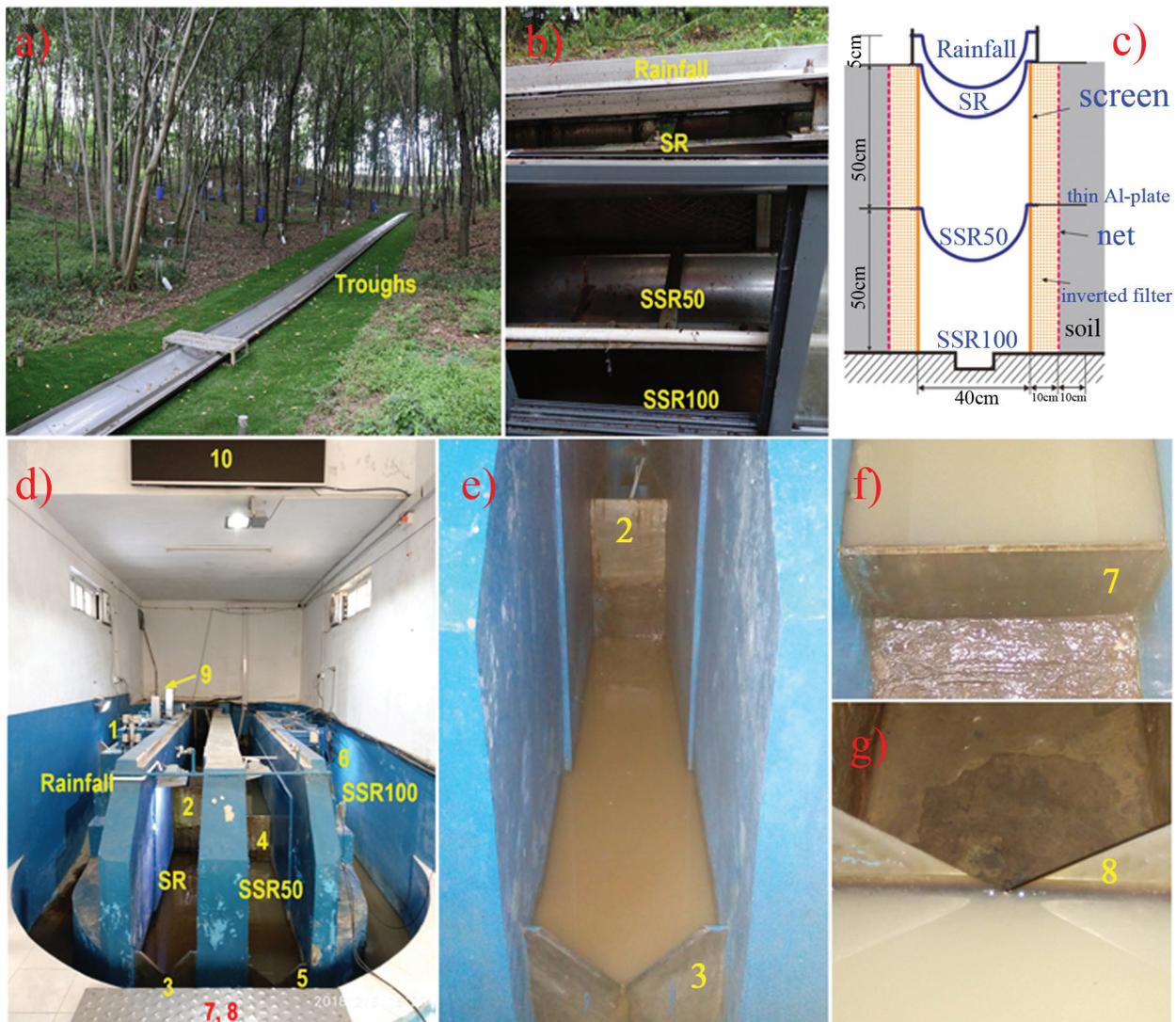


Figure 5. Instrumentation for runoff measurement in Nandadish: (a) Main trench with troughs (not shown), (b) the branch trench with four troughs (previously **Figure 13c**), (c) schematic figure illustrating various troughs, (d) discharge measurement structures for different runoff components from troughs 1 for rainfall; 2 and 3 for surface runoff; 4 and 5 for interflow (50 cm below the soil surface); 6 for interflow and groundwater flow (down to bedrock); 7 and 8 for total runoff (weirs are shown (f) and (g)). 1, 3, 5, 6, and 8 are 90° V-notch weir; 2, 4 and 7 are the full width rectangular weirs; 9 is the probe-type water level gauge; 10 is a video for monitoring the runoff processed, (e) combination of a 90° V-notch weir and a full width rectangular weir for SR, SSR50, and the total runoff, (f) the full width rectangular weir for total runoff, (g) the 90° V-notch weir for total runoff.

station, three trees of about 20 years were included, and three tipping bucket flow meters (0.4 L per bucket) were installed to measure the stem flow of each tree. A closing apparatus like a roof was explored to collect the total through rain. This apparatus is named as “collecting roof”. The collecting roof with a large area will result in a total amount of through rain when strong rainfalls occur, and thus large flow rates appear in the two outlets of the collecting roof. Two larger tipping bucket flow meters (2.0 L per bucket) were installed in the two outlets to measure flow rates. In addition to measure stem flow and through rain, a tipping bucket rain gauge was laid over the trees to record the rainfall inputting the rainfall station. According to water balance, the rainfall over the trees equals to the sum of stem flows, through rain and interception of trees.

2.2.2. *Runoff*

The surface and subsurface runoff are monitored directly via four layers of troughs fixed in a trench with a gradient of 6.7% (**Figure 5a**). These troughs are stacked on top of each other to capture rainfall, surface, and subsurface flows (**Figure 5b** and **c**): the uppermost trough captures rain; the next lower trough captures surface runoff (SR); and the two lower troughs capture subsurface flow from soil layers spanning the depths of 0–50, and 50–100 cm, inferred as SSR50 and SSR100 troughs. SSR50 and SSR100 troughs have 20-cm stainless lips that extend horizontally into the soil layer to prevent leakage between layers (**Figure 5c**). Waters captured in troughs are routed into a gauging room and measured by 90° V-notch and rectangle weirs (**Figure 5d** and **e**). For SR and SSR50, 90° V-notch and rectangle weirs are combined to measure discharge: when the large discharge occurs (correspondingly the water head above the rectangle weir is higher than 5.0 cm), the V-notch weir fails to measure discharge and the rectangle weir performs better; when the water head above the rectangle weir is lower than 5.0 cm, the discharge is measured more accurately by the V-notch weir than the rectangle weir. For rainfall and SSR100, only V-notch weir is used due to their less discharge compared with that of SR and SSR50. The trough SSR50 previously is located at 30 cm below the ground surface, this depth was extended to 50 cm during renovation due to the big changes happened to the growing of plants together with the deeper extension of their root system as described in **Figure 5f**.

2.2.3. *Soil moisture*

A network of 34 profile soil moisture sensors (SM-1, ADCON, same as those installed in Hydrohill, see latter) were installed in the different depths of soil. The number of profile soil moisture sensors with a depth at 90, 120, and 150 cm below the ground surface are 9, 10, and 15 (**Figure 6a**). The previous network of 34 access tubes (1982–1994) for neutron moisture gauge from UK Institute of Hydrology is shown in **Figure 6c**, the construction of access tube is shown in **Figure 6e**, while the standards of soil moisture for the calibration of neutron moisture gauge in a special laboratory are shown in **Figure 6f**.

2.2.4. *Groundwater*

For groundwater monitoring, there are 34 galvanized tube wells intersecting through the soil till the bedrock (**Figure 6b**). Water table measurement is performed with 30 level sensors (LEV1, ADCON, see later in Hydrohill). The previous network of wells for groundwater monitoring and sampling (1982–1994) is shown in **Figure 6c**, while the construction of well is shown in **Figure 6d**.

2.2.5. *Sap flow*

Sap flow is measured by Granier-type thermal dissipation probes (TDP) (Yugen, Beijing, China) that were installed in the sapwood of sample trees. A set of TDP includes a heated needle above and a reference needle below (**Figure 7a**). The sap flow velocity is calculated based on the temperature difference between the two needles. After the corky bark within a rectangular with a wide of 4 cm and tall of 10 cm was shaved off, the two probe needles

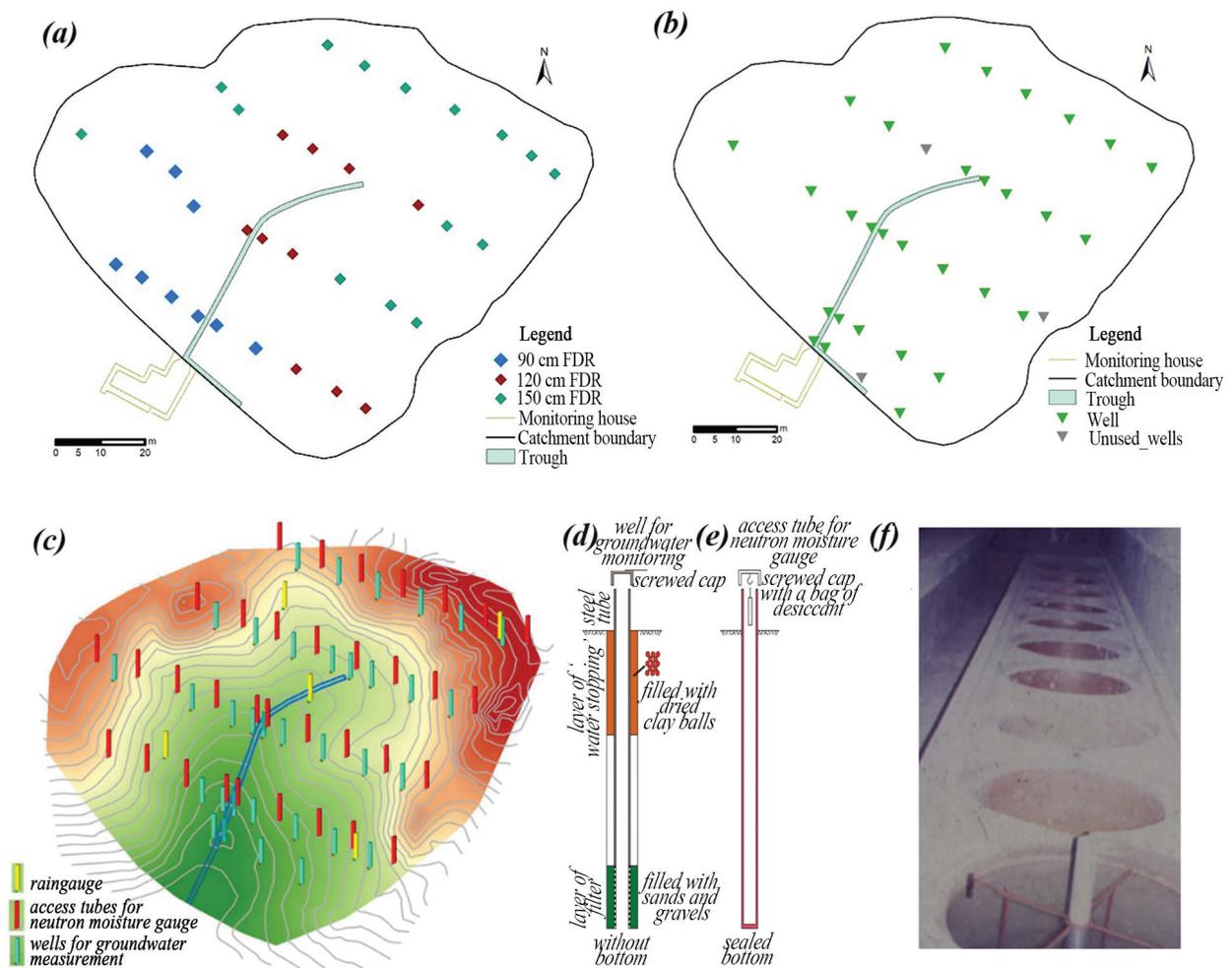


Figure 6. (a) Locations of profile soil moisture sensors with different depths: 90, 120, and 150 cm (since 2012); (b) network of wells for groundwater monitoring and sampling (since 2012); (c) previous network of access tubes for soil moisture monitoring and that of wells for groundwater monitoring (1982–1994); (d) construction of groundwater monitoring well; (e) construction of access tube for neutron moisture gauge (1982–1994); (f) standards of soil moisture with volumetric contents from 100 to 3% in a special laboratory for the calibration of neutron moisture gauge.

was inserted into the sapwood approximately 5 cm apart vertically. The reflective bubble shield was wrapped around the TDP probe to avoid monitoring errors caused by direct sunlight and rainfall leaching (**Figure 7b**). In the Nandadish catchment, totally 24 sets of TDPs were installed for 12 trees from 5 species, including three *Quercus acutissima* Carruth, three *Broussonetia papyrifera*, two *Populus L.*, two *Celtis L.*, and two *Melia azedarach L.*, to match the sapwood width of different tree species with different DBH, three different lengths of the probe (TDP10, TDP20, and TDP30) were adopted. All of the TDPs were installed about 145 cm above ground, and on both of the south and north sides of each sample tree. The temperature difference between the two needles was scanned at 1 min intervals, and the 10 min average value was recorded by a data logger (CR1000, Campbell, USA Scientific Inc., Logan, UT, USA).



Figure 7. Installation of thermal dissipation probes: (a) a set of TDP includes a heated needle (1) and a reference needle (2); (b) the reflective bubble shield (3) was wrapped around the TDP probe to avoid monitoring errors caused by direct sunlight and rainfall leaching, and a collection collar (4) for stem flow was installed above the TDP to stop stem flow entering.

2.3. Water sampling

Water samples from precipitation, runoffs, and plants were collected. Rain water samples were collected via a specially designed rain gauge and a standard rain gauge, which were installed on the roof of the gauging room (**Figure 8a**). The specially designed rain gauge is capable of collecting rain samples at 1-hour interval, while the standard rain gauge collects the mixed sample of each rain event. A batch sampling system is designed and constructed based on the negative pressure to easily and fast collect the water samples of runoff components of SR, SSR50, and SSR100 (**Figure 8b**). Water samples for runoff components are collected also via a stainless steel tube head fixed at the connection trough before the runoff reaches the ponding of the weir.

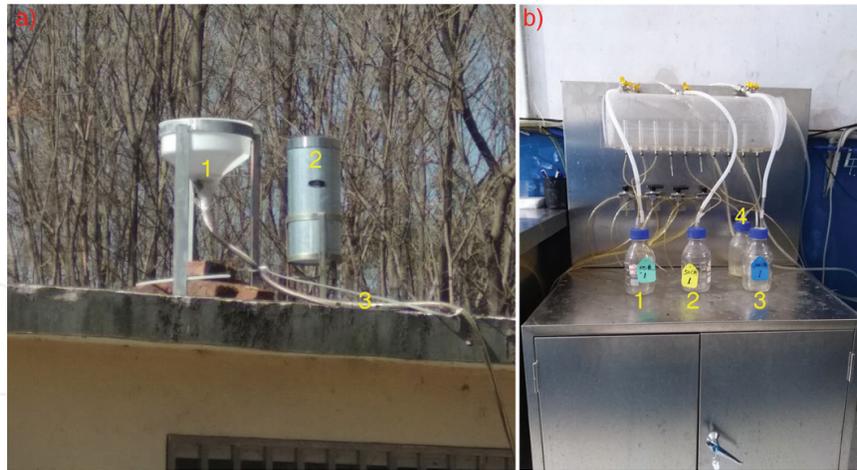


Figure 8. Water sampling in Nandadish: (a) sampling for precipitation, 1-a specially designed rain gauge capable of collecting rain samples at one-hour interval, 2-a standard rain gauge collecting the mixed sample of each rain event, 3-a tube directing rain water into a sampling bottle at the gauging room; (b) sampling for runoff components, 1-a sample bottle for SR, 2-a sample bottle for SSR50, 3-a sample bottle for SSR100, 4-a safeguard bottle.

3. Practice on the WHES: II–Hydrohill, an artificial catchment

3.1. The construction of Hydrohill

The artificial catchment Hydrohill of CHL was designed by Wei-Zu Gu during 1975 while he came back from his peasant life, kindly accepted and supported by Chuzhou administrator Mr. Wu-Min Cao for the laying down of both the Hydrohill and Nandadish on 1978. NHRI completed it and start running with data collection since July, 1982. The technological process can be sketched out summarily as follows.

(1) *Site selection and clearance*: A southeastward hillslope on a small hill, which is protruding integrally outwardly from its main area was selected for our Hydrohill due to its main geologic setting of andesitic tuff with altered volcanic rock. The space of this slope is enough for our initial design including in total three sister catchments with different characters each other. Moving away all the deposits including the weathered rock until the exposure of fresh bedrock, the site of clearance with area of ca 4700 m² was then prepared, however, only one catchment was constructed; (2) *Artificial aquiclude and surrounding wall*. A concrete aquiclude with two intersecting slopes dipping toward each other at 10°, an overall downslope gradients of 14°, and the longitudinally extending rectangular drainage trench etc. are constructed following the integral design of Hydrohill (**Figure 9a**). After that, an impermeable wall was set up on this aquiclude across the catchment boundaries (**Figure 9a**) aimed at enclosing the catchment to prevent any lateral exchanges of underground flow. These were completed during 1978 with its bird's eye view shown in **Figure 9b**. (3) *Soil filling*. An agricultural land was selected for the soil source of Hydrohill, a soil profile at the agricultural site with depth ca 1.5 m below the ground surface was dug for general observations, and undistributed soil of different layers were sampled for bulk density using current method. After that, the soil of the agricultural site was started to remove from its top horizon of about 10 cm in depth; it was piled up at a place close to Hydrohill, covered and marked. Then, the deeper parts of the soil were taken layer-by-layer every 20 cm and piled up, covered, and marked again. During soil filling



Figure 9. Constructions of Hydrohill. (a) the artificial aquiclude and surrounding wall; (b) view of the completed concrete aquiclude and wall; (c) view of the artificial catchment while soil was filled up, it was in idle for 3 years waiting for the physical improving of filling soil; (d) setting up monitoring networks for both saturated and unsaturated zone; (e) set drainage trenches; (f) the splicing fiberglass troughs and some steel supports; (g) the rectangular bottom trough for SSR100 and steel supports for the setting of SSR60 trough above it; (h) the gap for inverted filter and the nylon net in preparing; (i) the stainless steel screen in preparation for setting; (j) a curved connection trough; (k) connection troughs in installing; (l) discharge measuring structures using V-notch based logarithm sharp crested weirs (1982–1995).

in the concrete framework of Hydrohill, it was started from the soil pile of the deepest layer, that is, 90–100 cm of the original soil layer, it entered first into the artificial framework, after this layer was filling up, it was sampled for bulk density check. Then, the next piles of soil and so on. The

workers are happy to follow our lazy filling and the time-consuming checking on depths and bulk density of whole area by paying hourly wages. After whole area was completed, it was allowed to settle for 3 years before equipped (**Figure 9c**), while the natural grasses were revitalized. We then have opportunity to remeasure the established bulk densities during first exaction for the main trench later during 1981, it is 1.44 g/cm^3 at the top soil of 0–30 cm, 1.42 g/cm^3 of the layer at the depth of 30–50 cm, 1.40 g/cm^3 of 50–75 cm, and 1.60 g/cm^3 of 75–100 cm. (4) *Setting up monitoring networks for both saturated and unsaturated zone*. Three networks including 22 wells for saturated water (groundwater) table measurements and groundwater sampling, 21 aluminum alloy access tubes for neutron moisture gauge were installed, all of them were drilled to the aquiclude (**Figure 9d**). The tubes for groundwater monitoring were slotted along the lowermost 20 cm and wrapped up by plastic net (**Figure 10a and b**). After installation into the drilling hole, the space around the slotted lengths were packed with sands to allow movement of groundwater to the well, however, the space above the slotted lengths should be carefully stuffed up by small dried clay balls to prevent any water other than groundwater intruding along the pipes (**Figure 10c and d**). Different from the tube for groundwater, the neutron access tubes should have an intact wall with sealed bottom, using threaded cap with a hanging pack of desiccant for sustaining a state of dryness in the tube (**Figure 6e**). A part of resulted networks is shown in **Figure 10d**. (5) *Drainage trenches*. After the installation of groundwater wells and access tubes, the drainage trenches including the main longitudinal trench and the side trench perpendicular to the main trench at the watershed outlet were dug up (**Figure 9e**). (6) *The layered troughs*. It was worked first from the bottom one. The splicing fiberglass troughs each 40 cm wide and some steel supports are shown in **Figure 9f**, **Figure 9g** shows the rectangular trough for SSR100 and steel supports for the setting of trough above it, that is, the SSR60. These troughs were constructed as shown in **Figure 11**, they were stacked on top of each other to create a set of long zero-tension lysimeters, each trough has a 20 cm aluminum lip that extends horizontally into the soil layer to prevent leakage between layers (**Figure 11**). (7) *The inverted filter*. There is a gap between the trough and the soil (**Figure 9h**) for the inverted filter (**Figure 11**) including the filling materials and the nylon net at the soil side and the stainless steel screen at the trough side (**Figure 9h and i**, **Figure 11**). (8) *The connection troughs*. With different curvatures, these troughs link the runoff troughs with the approaching part of measuring structures individually (**Figure 9j and k**). (9) *Discharge measuring structures*. We combined the V-notch sharp crested weir and the logarithm-notch sharp crested weir together, and defined it as the V-notch based logarithm sharp crested weir (**Figure 9l**) for discharge measurement of SR and SSRs. (10) At last, 30 hole sites for tensiometers at different depths together with the connection tubes from tensiometer to the scanning recorder were set up (**Figure 10e**).

After the finalization of construction, the artificial Hydrohill catchment has a drainage area of 490 m^2 (horizontal projection), 512 m^2 (inclined surface) as shown in **Figure 12** including its previous version since 1982 (**Figure 12a–d**), and the renovation version (**Figure 12e–h**). The lengths of the longitudinal trough (5 in **Figure 12b, c, e, g**) and the transverse trough (4 in **Figure 12b and e**) are 29.4 and 6.8 m, respectively. The width of the trough is 0.4 m. The horizontal projected area of the trough is 13.8 m^2 , and thus horizontal projected area of soil surface is 487.2 m^2 .

Recently, the average thickness of the soil is lower than that in 1982, especially in the upstream (**Figure 13**). To date, the average thickness of the soil in the upstream ($\sim 85 \text{ cm}$) has been less than that in the downstream ($\sim 105 \text{ cm}$) and that in the midstream ($\sim 103 \text{ cm}$).

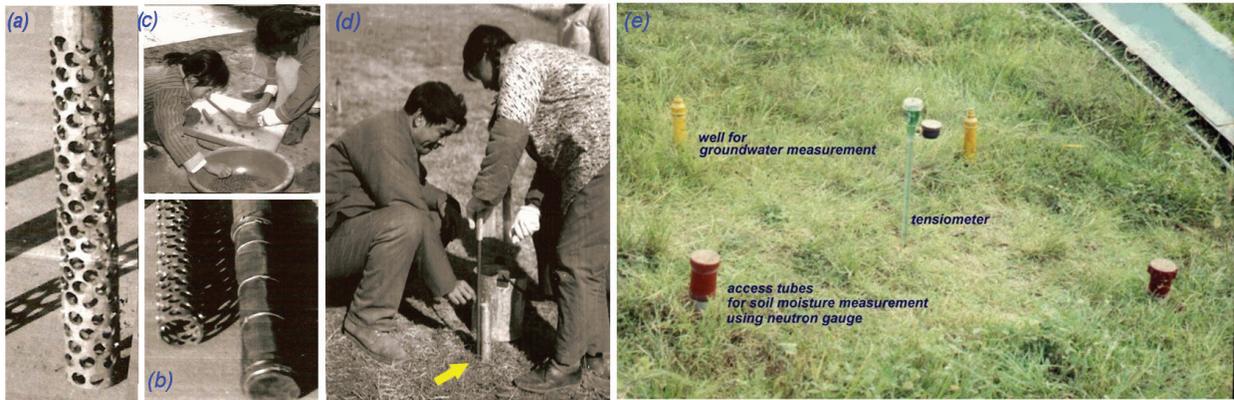


Figure 10. Construction of groundwater monitoring well. (a) the slotted part of steel tube; (b) the tube was wrapped up by plastic net; (c) making clay balls for using; (d) during installing, the space between the tube and drilling hole above the slotted lengths (shown by a yellow arrow) should be carefully stuffed up by small dried clay balls using a special designed tool. This picture is shown in commemoration of the late prof. M-Q Lu (left) of Nanjing University for his efforts and contributions. (e) a part of resulted networks showing well for groundwater, access tube for neutron moisture gauge and the tensiometer with connection plastic tubes to the scanner.

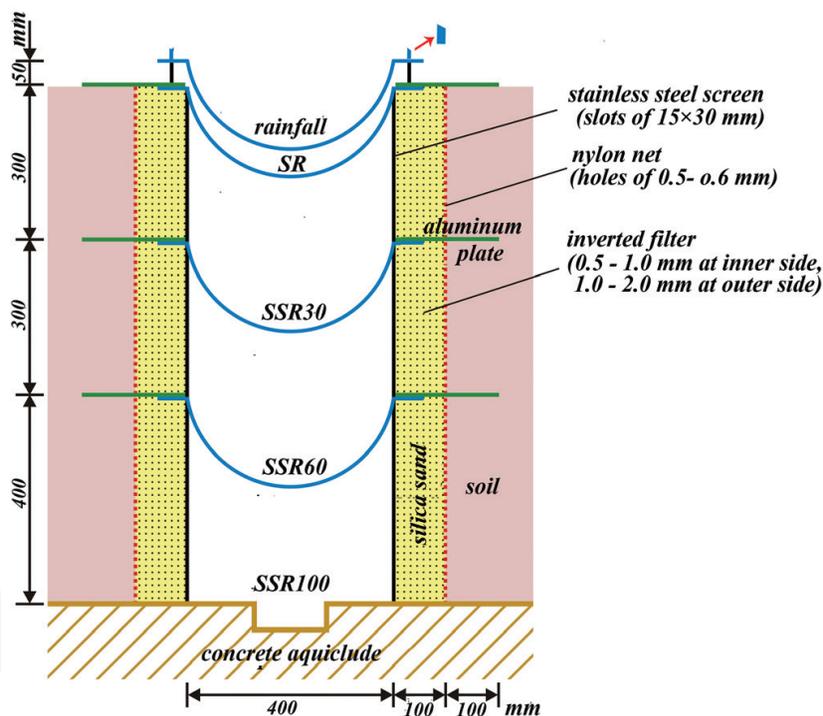


Figure 11. Construction of troughs. SR-trough for surface runoff; SSR30-trough for subsurface runoff at the depth of 30 cm below the ground surface; SSR60-that at the depth of 60 cm; SSR100-that at the depth of 100 cm.

3.2. Instrumentation in Hydrohill catchment

3.2.1. Precipitation

To monitor the distribution of rainfall and test the spatial uniformity of the rainfall generated by a rainfall simulator, 12 standard rain gauges (**Figure 14a** and **b**) and 5 tipping bucket

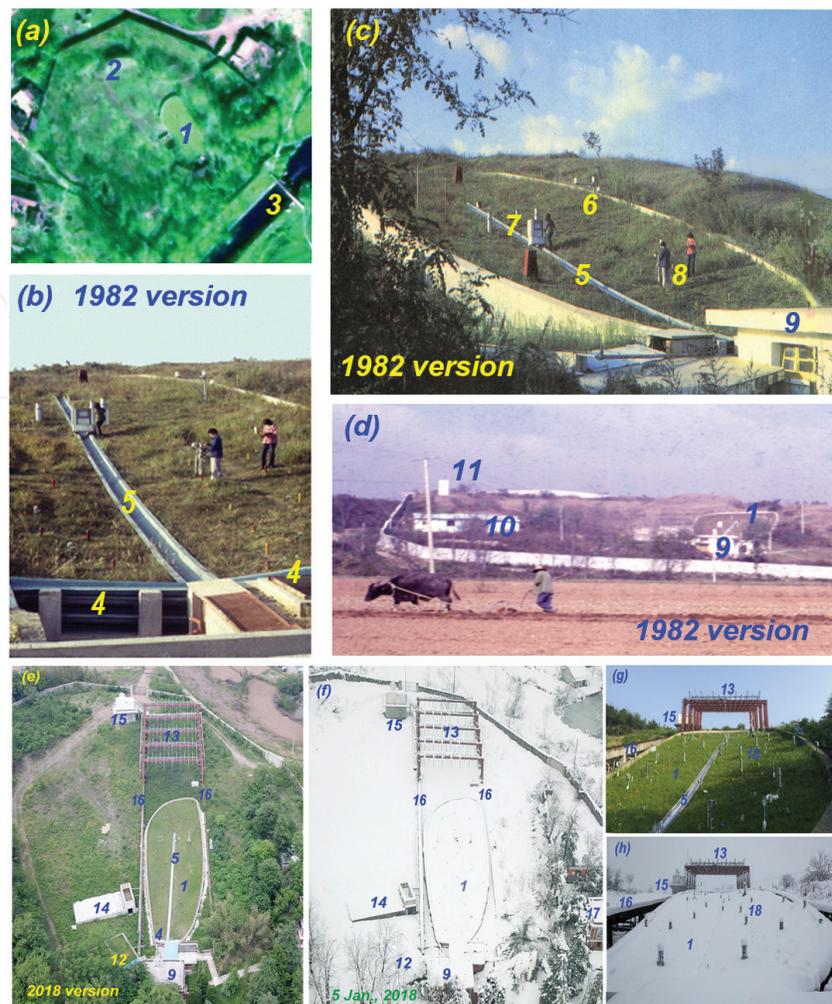


Figure 12. Finalization of the artificial catchment Hydrohill, its previous version (1982–1995) and renovation version (since 2012). (a) a satellite image showing Hydrohill and the whole hillslope area to be excavated of ca 4700 m²; (b) and (c) the previous version of equipped Hydrohill; (d) the environment of Hydrohill. 1-land surface of Hydrohill; 2-an uncompleted artificial catchment; 3-the outlet of the Bloomhill Basin showing a discharge measuring structure of the gauging station; 4-the side trench perpendicular to the main trench at the watershed outlet; 5-the main longitudinal trench with layered troughs; 6-energy budget monitoring apparatus; 7-a scanning recorder for soil water potential from distributed sensors; 8-the neutron moisture gauge is in operation; 9-underground house for the discharge measuring structures; 10-laboratory for the calibration of neutron moisture gauge (1982–1988); 11-water supply tower; 12-two lysimeters with layered runoff troughs, 4 × 8 m² each, two different soils; 13-movable rainfall simulator at rest; 14-a reservoir for water supply of rainfall simulator; 15-a dual polarization Doppler precipitation radar for the areal precipitation monitoring of the Bloomhill Basin with drainage area of 80 km²; 16-tracks for the moving of rainfall simulator; 17-laboratory for instrument measuring of isotopes; 18-various monitoring wells, sensors, samplers.

rain gauges (**Figure 14a** and **c**) were installed within the catchment. To test the measurement accuracy of the tipping bucket rain gauge, a 10-L plastic pot was connected with the drainage holes in the bottom of the tipping-bucket rain gauge (**Figure 14c**).

3.2.2. Runoff components

The uppermost trough (**Figures 11** and **15**) collects rain; the next lower trough collects surface runoff (SR); the three lower troughs collect subsurface flow from soil layers of the depths of 0–30, 30–60, and 60–100 cm (inferred as SSR30, SSR60, and SSR100 troughs).

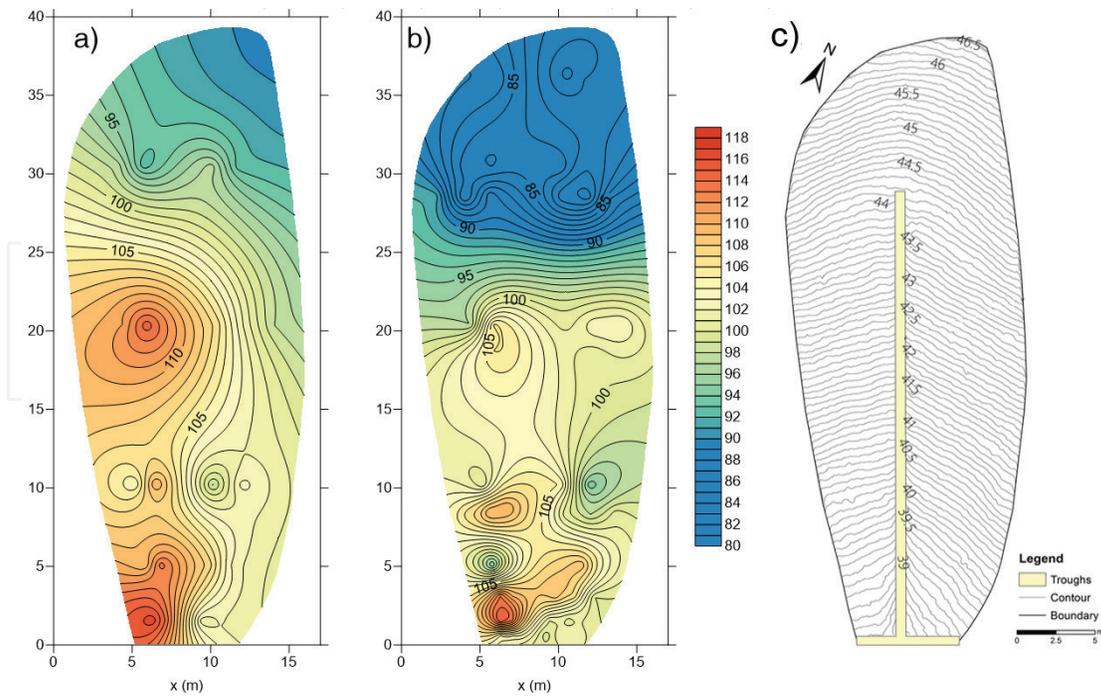


Figure 13. Changes in the filling soil thickness of the Hydrohill catchment: (a) Isolines of catchment soil depth in 1982; (b) that in 2017; (c) hypsographic map of soil surface obtained from a three-dimensional laser scanner (2017).



Figure 14. Instrumentation for precipitation measurement in Hydrohill: (a) locations of 12 standard rain gauges and 5 tipping bucket rain gauges; (b) a standard rain gauge; (c) a tipping-bucket rain gauge. 1-external structure, 2-internal structure, 3-a plastic pot used to collect total precipitation of each event.

Runoff collected from trough SSR30 is the interflow from the unsaturated zone, but that from trough SSR60 will depend on the depth of the saturated zone due to the fluctuation of groundwater table. In case when the saturated zone table (plus its capillary fringe) is lower than the trough, then the runoff measured in SSR60 is the interflow from the unsaturated zone; otherwise, it will be the groundwater flow from the saturated zone. Water collected in troughs is routed by measuring structures as shown in **Figure 15** (the renovation version). For each weir, a pressure-type water level gauge (LEV1, ADCON) and a probe-type water level gauge (NKY08-2, NHRI) are adopted to simultaneously measure the water head above the weir.



Figure 15. The discharge measuring structures of renovation version and the instrumentation for its water heads. 1-probe-type water level gauge; 2-tracking gauge for the real-time water head process.

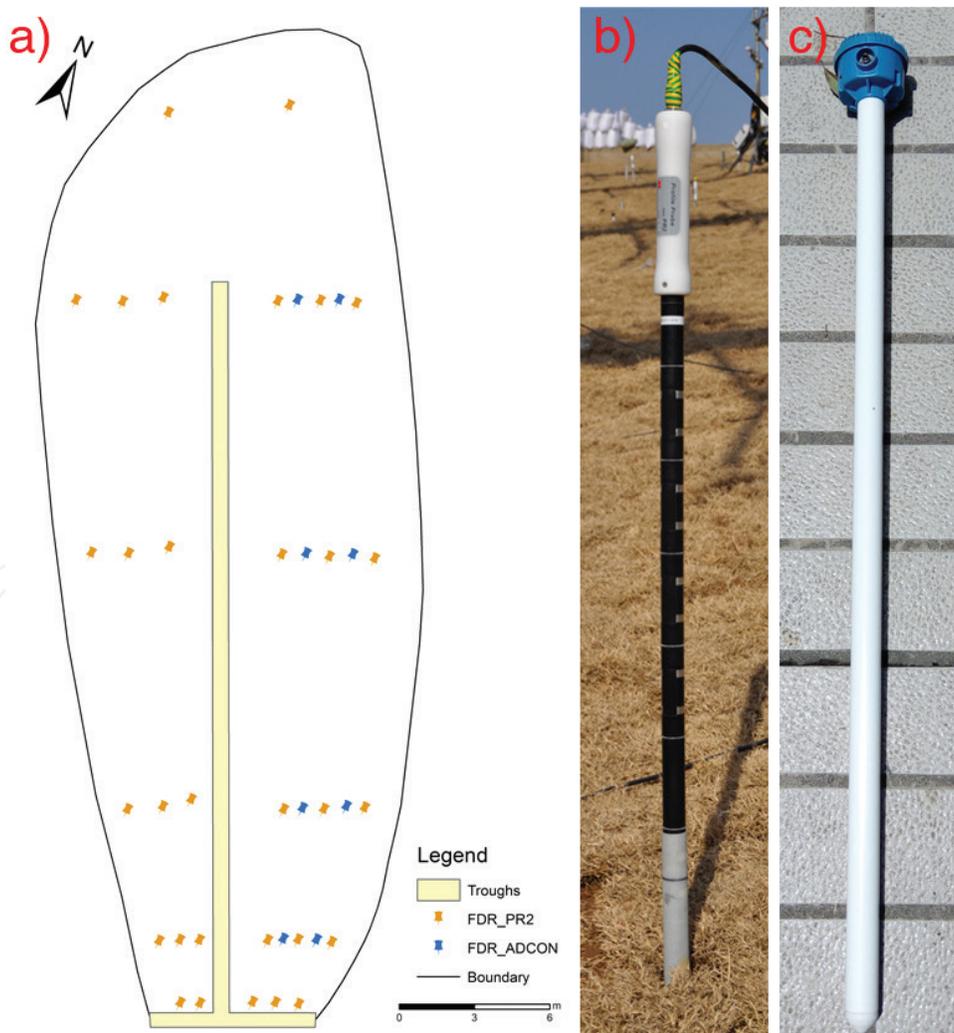


Figure 16. Instrumentation for soil water measurement in Hydrohill catchment: (a) the locations of the soil moisture sensors and soil water sampling points; (b) the UK soil moisture sensor (PR2, Delta-T, UK); (c) the German soil moisture sensor (SM-1, ADCON, Germany).

3.2.3. Soil moisture

A network of 21 aluminum alloy access tubes for neutron moisture gauges were constructed previously (1982–1995). Since then, all aluminum alloy access tubes have been displaced with 31 profile soil moisture sensors (PR2, Delta-T, UK), with their locations shown in **Figure 16a**. Each sensor has six sensor points located at the 10, 20, 30, 40, 60, and 100 cm (**Figure 16b**). Another six profiles with another kind of soil moisture sensors (SM-1, ADCON, Germany) were installed as well. This type of SM-1 has nine sensor points located at the 10, 20, 30, 40, 50, 60, 70, 80, and 90 cm (**Figure 16c**).

3.2.4. Groundwater

An array of 22 galvanized tube wells intersect through the soil till the concrete aquiclude (**Figure 17a**). Water table measurement is performed with level sensors (LEV1, ADCON, Germany, see **Figure 17c**).

3.2.5. Evaporation from land surface

An energy budget system (**Figure 18a**) and an eddy covariance system (**Figure 18b**) were mounted for accurate monitoring evaporation. The systems were equipped with the following sensors: one 3-D ultrasonic anemometer (C150, Campbell, USA), one CO₂/H₂O infrared gas analyzer (Campbell, USA), three air temperature and moisture sensors (HMP155A, Vaisala, Finland), four-way net radiometers (CNR4, Kipp and Zone, Netherlands), one ground surface infrared temperature sensor (SI-111, Campbell, USA), five soil temperature sensors (109, Campbell, USA), five soil moisture sensors (CS616, Campbell, USA), and four soil heat flux sensors (HFP01SC, Huksflux, USA). In addition, a small aperture scintillometer (SLS-40A, SCINTEC, Germany, see **Figure 18c**) is to be installed with its transmitter unit and receiver unit outside the Hydrohill catchment.

3.2.6. Movable rainfall simulator

A movable rainfall simulator system (**Figure 19a**) was designed and constructed over the Hydrohill catchment in 2012. This system consists of five sub-systems, which can be controlled independently by the control platform (**Figure 19d**) to generate different rainfall intensities (10–200 mm/h) via the combination of different sizes of sprinkle nozzles (**Figure 19e**) with regulations of water pressure. **Figure 20** shows the schematic diagram of the rainfall simulator system. The rainfall area of this modeling system is 656 m², which can effectively cover the Hydrohill catchment (**Figure 19b**), and the spatial uniformity of the simulated rainfall is larger than 0.8. After the simulating rainfall event is finished, the rainfall simulator system can be moved to the outside of Hydrohill catchment (**Figure 19c**).

3.2.7. Water sampling

3.2.7.1. Water sample types and analysis indexes

Water samples from precipitation, runoffs, soil, groundwater, and plants were collected. Analysis indexes for water samples are included in three categories:

- ① General parameters: electrical conductivity (EC), pH, dissolved oxygen (DO), and water temperature;
- ② Hydrochemistry: K^+ , Na^+ , Ca^{2+} , Mg^{2+} , HCO_3^- , CO_3^{2-} , Cl^- , NO_3^- , SO_4^{2-} , and SiO_2 ;
- ③ Isotopes: ^{18}O , 2H , and ^{15}N .

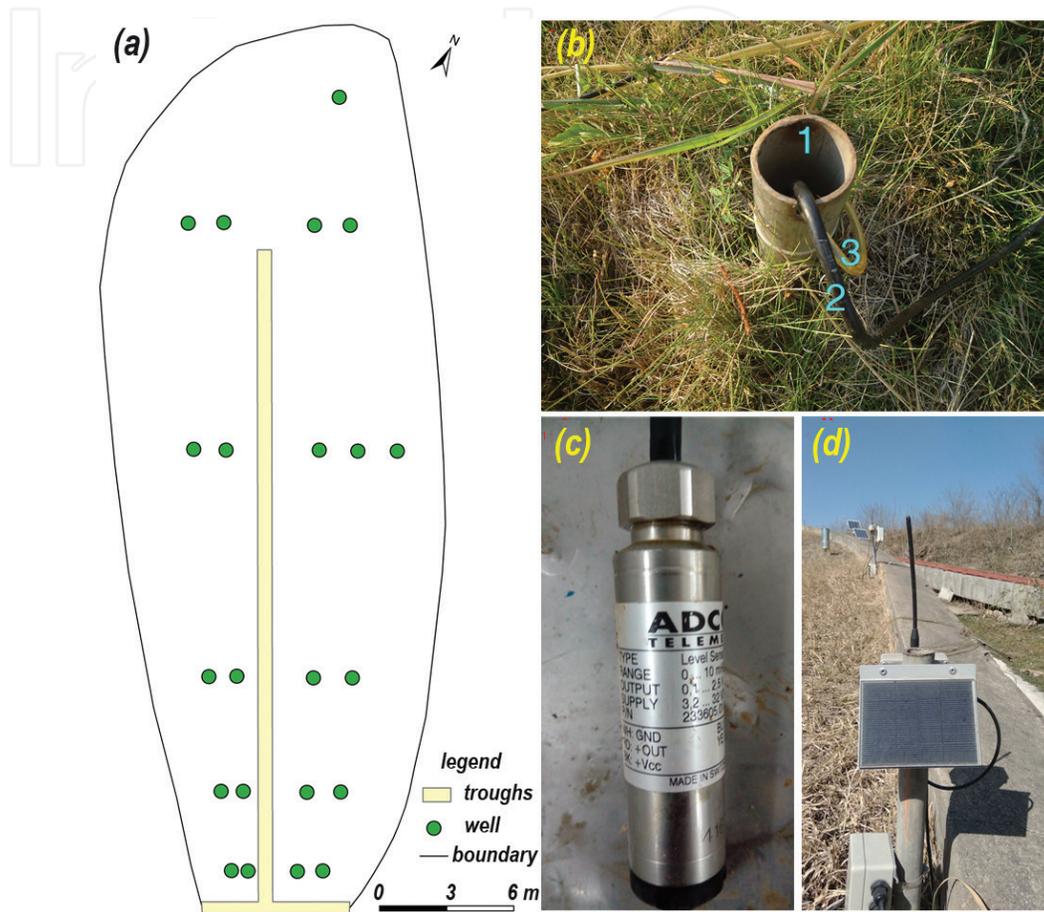


Figure 17. Instrumentation for groundwater measurement in Hydrohill catchment: (a) locations of the monitoring wells; (b) the monitoring well (1-the galvanized tube, 2-the connection cable of the level sensor, 3-a plastic tube for sampling groundwater); (c) the level sensor which is a pressure transducer with atmospheric pressure compensation; (d) a remote terminal unit (RTU) receive the data from the groundwater level sensors (LEV1, ADCON, Germany) and send the obtained data to the gateway via radio together with that from soil moisture sensor as shown in **Figure 16** (SM-1, ADCON, Germany).

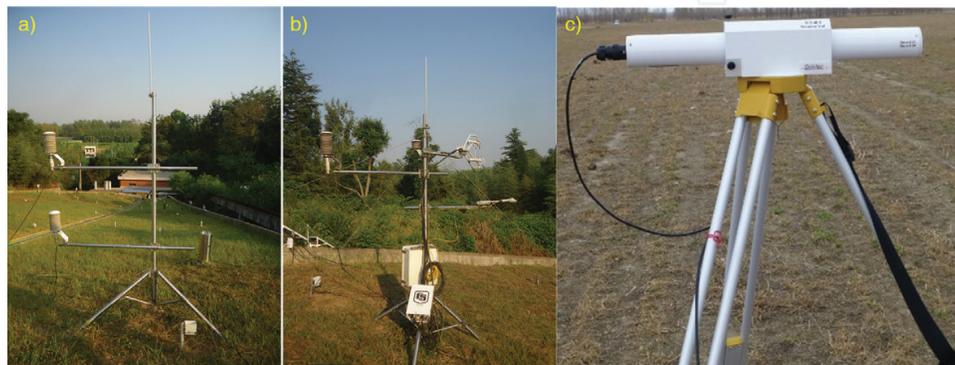


Figure 18. Instrumentation for the evaporation from ground surface in Hydrohill. (a) An energy budget system; (b) an eddy covariance system; (c) a small aperture scintillometer.



Figure 19. Rainfall simulator system in Hydrohill: (a) before the rainfall simulating; (b) during the rain simulating; (c) after the rainfall simulating event (1-an impounding reservoir supplying the rainfall simulator system, 2-a water supplying pipe); (d) the rainfall simulator control platform located in the gauging room; (e) combination of different sizes of sprinkle nozzles.

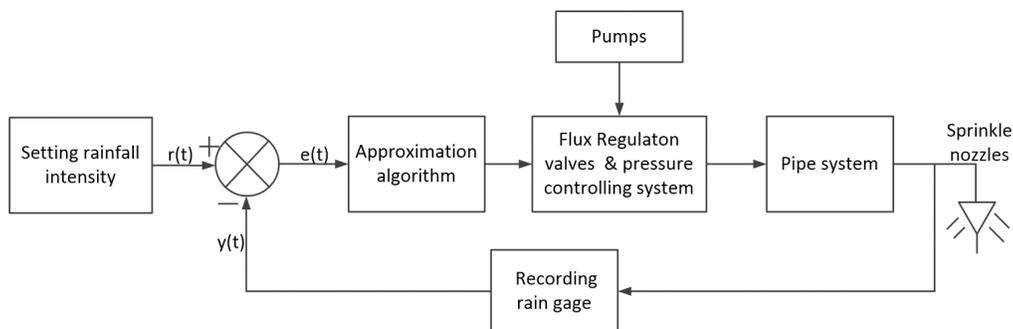


Figure 20. Schematic diagram of the rainfall simulator system.

3.2.7.2. Sampling for precipitation

Rain water samples were collected using two methods: first is via the rainfall trough, which serves as a rain gauge distributed longitudinally with total area of 13.8 m² (**Figure 21a**), the second is via a specially designed rain gauge with a diameter of 40 cm, which was installed on the roof of the gauging room (**Figure 21b**). The result from these two methods shows that they are similar to each other with only few exceptions (**Figure 22**).

3.2.7.3. Sampling for runoff components

To easily and to fast collect water samples of different runoff components in Hydrohill, a batch sampling system is designed and constructed based on negative pressure (**Figure 23**). The schematic of the batch sampling system is shown in **Figure 23a**. Water samples for runoff components are collected via a stainless steel tube head fixed at the connection trough before the runoff reaches the ponding of the weir (**Figure 23c**).

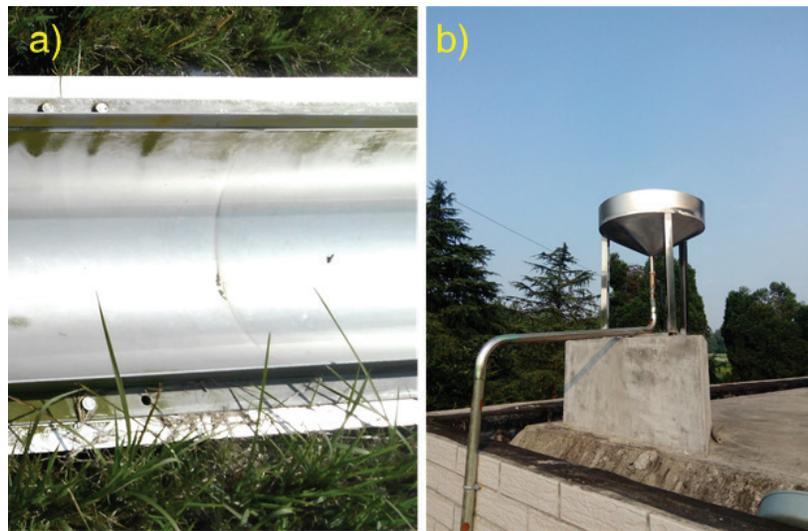


Figure 21. Two methods for rainfall sampling: (a) method-1 using the rainfall trough as a longitudinal rain gauge; (b) method-2 using a specially designed rain gauge.

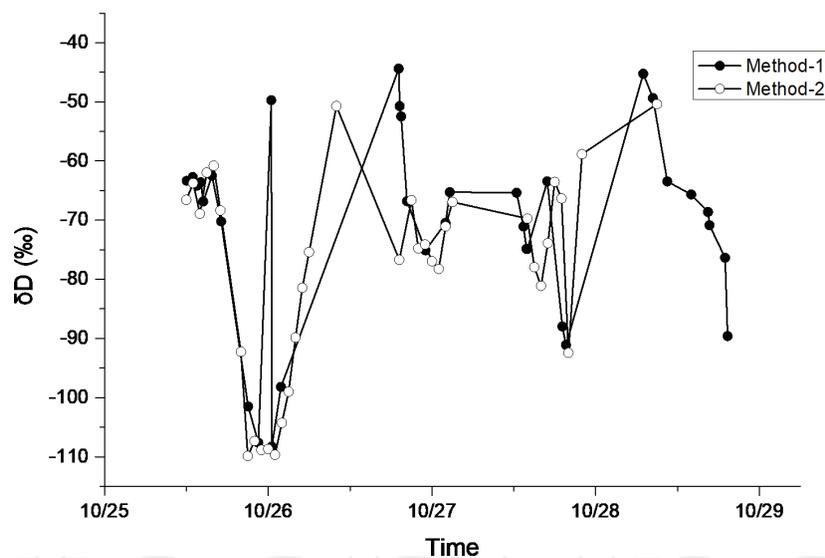


Figure 22. Comparison of results from two methods for rainfall sampling. Method-1: Using the rainfall trough; Method-2: Using a specially designed rain gauge. Data is resulted from a rainfall event in 2016.

3.2.7.4. Sampling for soil water and groundwater

To sample the soil water, 31 suction lysimeters (**Figure 24a** and **d**) were installed at three depths: 9 at 15 cm, 12 at 45 cm, and 10 at 80 cm. To keep the synchronism of sampling, a batch sampling system is designed and constructed based on negative pressure (**Figure 24b** and **e**). Groundwater samples of 22 points were collected with the tubes previously fixed on the level sensors (**Figure 24a** and **f**). Similarly, a batch sampling system is designed and constructed based on negative pressure to keep the synchronism of sampling groundwater (**Figure 24c** and **d**).

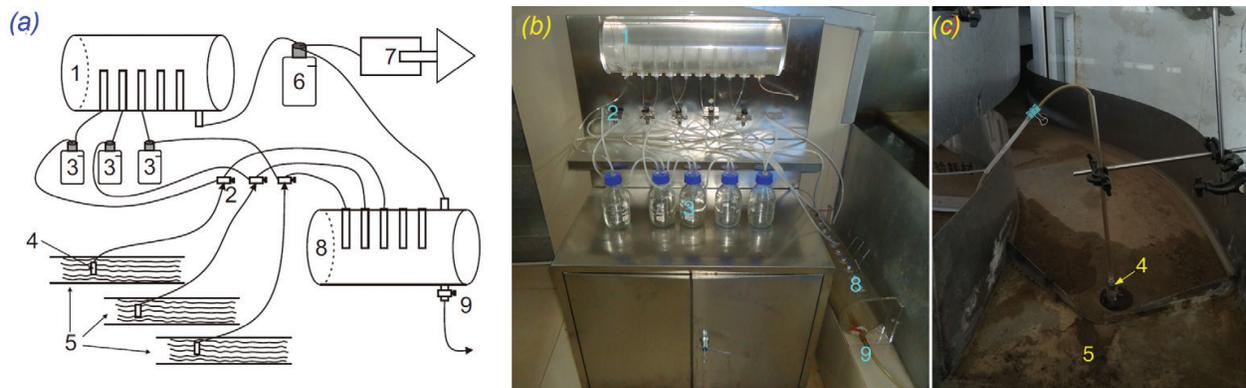


Figure 23. Instrumentation for sampling runoff components in Hydrohill: (a) the schematic of the batch sampling system; 1-the negative-pressure extender, 2-three-way valve, 3-sample bottles, 4-a stainless steel tube head enclosed by a yarn to stop sand and litter into the sampling tube, 5-troughs, 6-a safeguard bottle, 7-a vacuum pump, 8-a container used to drain the old water in the tubes, 9-a valve to drain the water in the container; (b) photo of a batch sampling system based on negative pressure; (c) a stainless steel tube head fixed at the connection trough before the runoff reaches the ponding of the weir.

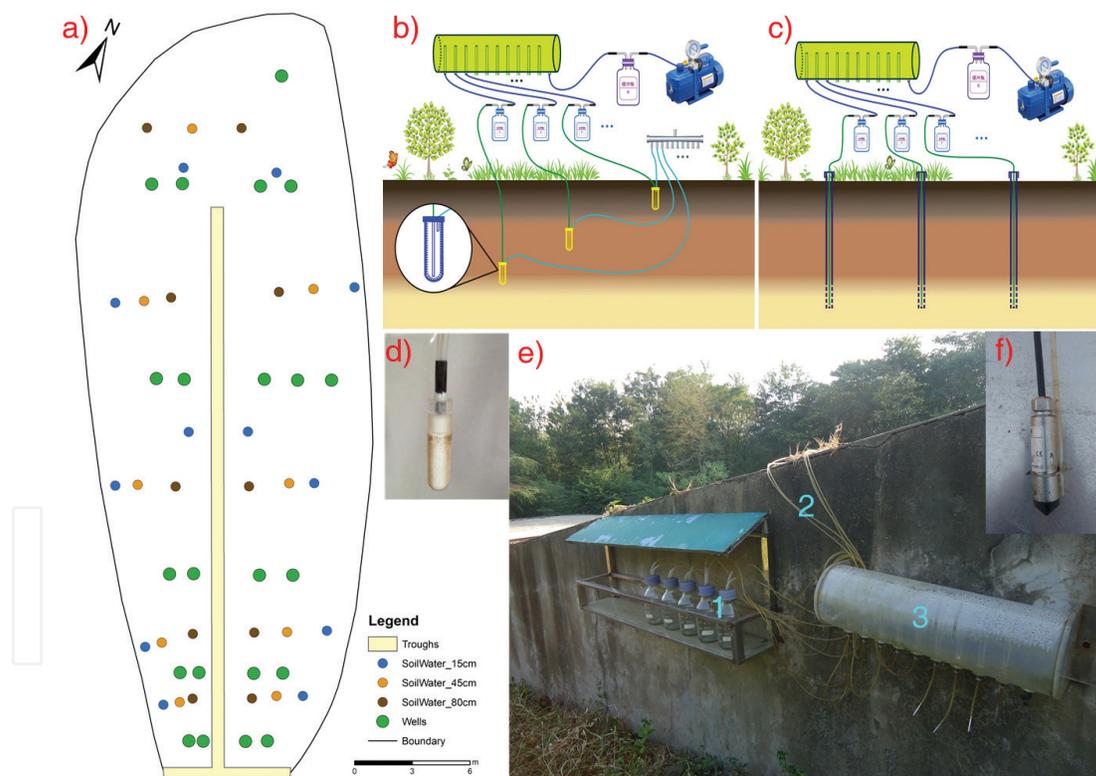


Figure 24. Instrumentation for sampling soil water and groundwater in Hydrohill: (a) locations of the sampling points of the soil water and groundwater; (b) schematic of a batch sampling system designed and constructed based on negative pressure for sampling soil water; (c) that for sampling groundwater; (d) a suction lysimeter; (e) photo of a batch sampling system designed and constructed based on negative pressure for sampling soil water and also for groundwater; (f) the tube previously fixed on the level sensor to sample groundwater. 1-sample bottles, 2-tubes connecting with suction lysimeters or groundwater wells, 3-the negative-pressure extender.

3.3. Analyses of water samples

3.3.1. General parameters

Electrical conductivity (EC) was measured in the field using a portable EC digital analyzer (HQ14d, Hach, USA). Dissolved oxygen (DO), pH, and water temperature were measured in the field using a multi-parameter digital analyzer (HQ40d, Hach, USA). These parameters were determined immediately after water samples had been collected.

3.3.2. Hydrochemistry

Most chemical analyses were undertaken at the Tiexinqiao experiment base of Nanjing Hydraulic Research Institute, China. All water samples were analyzed within 2 weeks of the date of collection. Concentrations of the major cations (Na^+ , K^+ , Ca^{2+} , and Mg^{2+}) were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OEC, see **Figure 25a**), and the anions (SO_4^{2-} , Cl^- , NO_3^- , and F^-) were analyzed by DIONEX ICS-2100 ion chromatography (**Figure 25b**). All samples were filtered through a $0.45\ \mu\text{m}$ filter before laboratory analysis. The analytical precision of the measurement of ions was determined by calculating the absolute error in ionic balance, and the analytical error was less than $\pm 2\%$ for the anions and between ± 1.5 and $\pm 4\%$ for the cations. HCO_3^- concentrations were determined by a titration assay on site or within 24 h of sample collection.

3.3.3. Isotopes

Soil and plant waters were previously obtained via a vacuum extraction system (LI-2000, LICA, China, **Figure 26a**). The $\delta^{18}\text{O}$ and δD of water samples determined using a liquid water isotope analyzer (908-0008, LGR, USA, **Figure 26b**) or a liquid–gas water isotope analyzer (L2120-i, Picarro, USA, **Figure 26c**). The dual isotopes of nitrate were prepared by quantitative bacterial reduction of nitrate to nitrous oxide (N_2O) using the denitrifier method followed by automated extraction and purification using Trace Gas Pre-concentrator unit (IsoPrime Ltd., Cheadle Hulme, Cheadle, UK) and analysis of the N_2O product using an isotope ratio mass spectrometer (GV, IsoPrime, **Figure 26d**). Four international nitrate (USGS-32, USGS-34, USGS-35, and IAEA-N3) and experimental reference materials that were treated identically with the water samples were used to calibrate the measured sample data. Each sample was measured in duplicate and the standard error was 0.3‰ for $\delta^{15}\text{N}\text{-NO}_3^-$ and 0.5‰ for $\delta^{18}\text{O}\text{-NO}_3^-$.

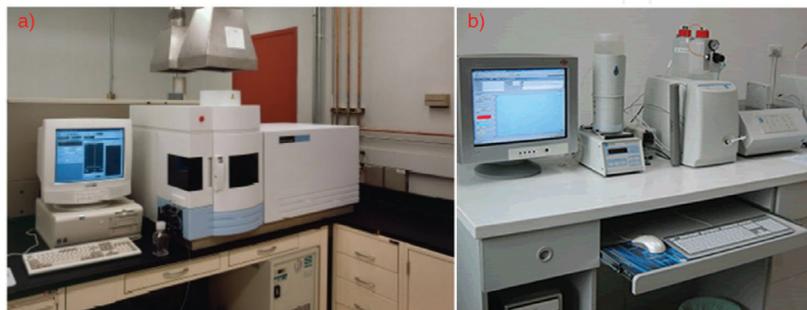


Figure 25. Instruments adopted in hydrochemistry analysis of water samples: (a) inductively coupled plasma optical emission spectrometry (ICP-OEC); (b) ion chromatography (ICS-2100, DIONEX, USA).

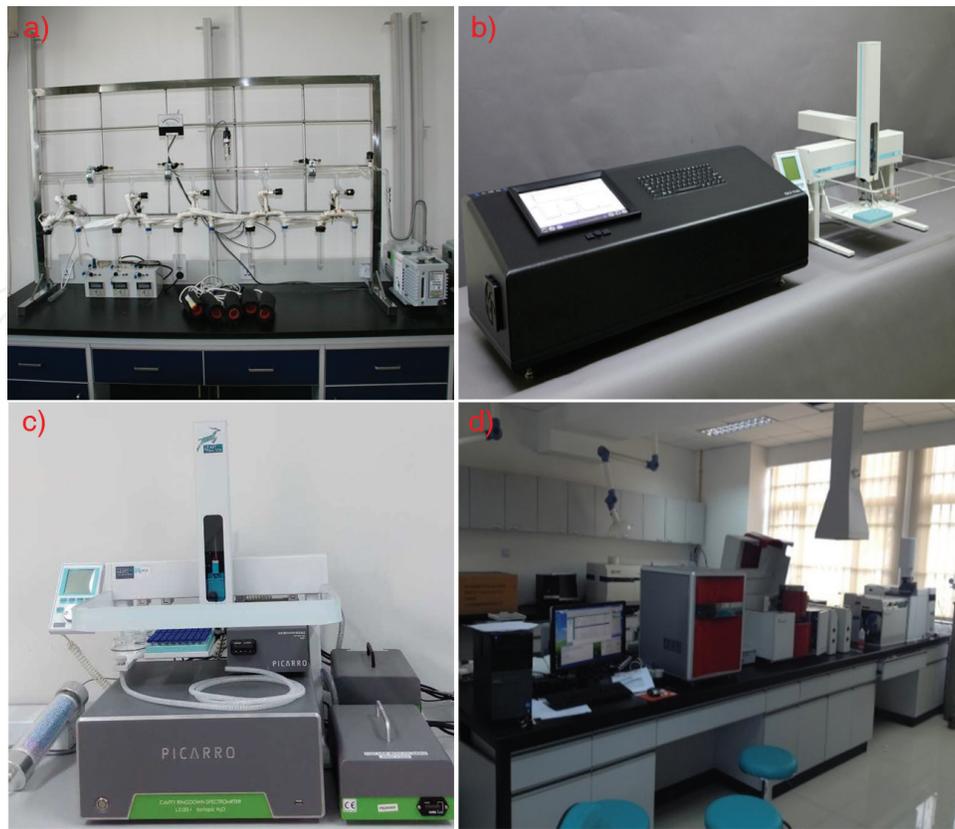


Figure 26. Instruments adopted in isotope analysis of water samples: (a) a vacuum extraction system (LI-2000, LICA, China); (b) a liquid water isotope analyzer (908-0008, LGR, USA); (c) a liquid-gas water isotope analyzer (L2120-i, Picarro, USA); (d) IsoPrime100.

4. Some results

4.1. Explore the possible paths

Aimed at ending the scientific stalemate on our watershed experimental studies. Since 1982, the origin of CHL, from classic natural experimental watershed, current pedon lysimeter, and the uncompleted experimental system until the Chuzhou WHES, various possible paths are tried for the emerging of some possible paths ([1–6]), to achieve hopefully the sustainable development of the watershed hydrological experimentation. It is found that the intermediate “mesos” including those of controlled-nature and artificial-nature with constrain and add complexity respectively, show its crucial importance for revealing the individual mechanisms hidden deep. Philosophically, it is “the golden mean between two extremes of character” in Book IV of his Ethics of Aristotle, and the idea of “holding the two extremes and using the middle impartial” in China for the “music” of our watershed experimental studies.

4.2. Explore the subsurface runoff components

- Direct measurement: After progressively improving, the method of longitudinal zero-tension lysimeter (layered trough) is used in catchment scale for the direct measurement of surface and subsurface runoff components ([1, 7]).

- **Runoff components:** Three components are identified including surface runoff (SR), interflow (IF) from unsaturated zone, and groundwater flow (GF) from saturated zone ([5–8]).
- **Amount proportion:** From 375 runoff generation-events (1982–1995), the total subsurface contribution accounted for 43% of total runoff, 27% of total runoff was contributed from the *direct interflow* from the unsaturated zone [9].
- **Patterns of rainfall-runoff process:** Four patterns are identified according to the dominated runoff components, surface flow or subsurface flow [9–11].
- **Rainfall-runoff correlation diagram:** scattering of data points including that of surface runoff very likely is caused by different runoff compositions of different sources of water rather than simply the rainfall characters or, the curve numbers [9, 12].

4.3. Explore the generation mechanisms of runoff components

Eleven mechanisms types have been identified including 4 of SR, 4 of IF, and 3 of GF [13, 14].

4.4. Explore the composition of pre-event water

- **Occurrence of pre-event water:** It is identified that the pre-event (“old”) water is frequent occurred even in the SR [11, 15].
- **Process of pre-event water:** A 4-year case studies show that the pre-event (old) water within 4 different runoff patterns accounted for 0–36% in surface dominated pattern and up to 60% in subsurface pattern, 47–77% and 21–75% the other patterns [9, 11, 15, 16].

4.5. Explore the hydrological puzzles

It emerges that the unsaturated zone is the gremlin, the key to revealing the hydrologic maze because it is closely related to the runoff composition, hydrological heterogeneity and the double paradox in catchment hydrology and hydrogeochemistry [6, 9, 17].

4.6. On some parameters

- ^{131}I tracing for infiltration and preferential flow [18, 19];
- Spatiotemporal distribution of soil water ^{18}O in Hydrohill catchment [9];
- Optimization selection of discharge measuring structures for the application of WHES [20, 21];
- Neutron gauging for vadose water and safety evaluation for users [22];
- Nuclear methods for the monitoring of evapotranspiration from land surface [23].

4.7. Basic research for applications

Preliminary methodological studies for applied hydrological projects

- Unreasonableness of current two-component isotope hydrograph separation [6, 24–26];

- Water tracing using uranium disequilibrium and other tracers for identification of water sources [27, 28, 29];
- Neutron activation for rain water, river water, and groundwater [30, 31];
- Isotope-In-Precipitation Network of China [32];
- Agricultural water demands [33, 34];
- Nonpoint source of agricultural area [35, 36].

4.8. The post graduates dissertations achieved by working in and/or main source from CHL

PhD dissertation

1993: Carol Kendall. Impact of isotopic heterogeneity in shallow systems on stormflow. University of Maryland.

2017: Meng Huang. Using isotopes to evaluate nitrogen sources and transformation processes in Chuzhou hydrological watershed. Hohai University.

Master dissertation

1986: Xue-Wen Wang. Study on the cropland evapotranspiration. Nanjing Institute of Meteorology.

1990: Jing Huang. Application of satellite image for the GIUH confluence model. Wuhan University, Wuhan Institute of Hydraulic and Electric Engineering.

1990: Shu-Qin Xie: Application of satellite imagine for the runoff generation using the SCS Model. Wuhan University, Wuhan Institute of Hydraulic and Electric Engineering.

2016: Niu Wang: Output characteristics of non-point source nitrogen and phosphorus load in Huashan Basin. Hohai University.

2017: Nuo Yang: Study on the tracing of precipitation and runoff in the Hydrohill Experimental Catchment using hydrochemistry and isotopes. Hohai University.

5. Conclusions

The construction and instrumentation of two typical parts of Chuzhou WHES are reviewed, including the Nandadish, a trial target for the CZEB, which is the type of so-called *controlled-natural*, and the Hydrohill, another trial target for CZEB, that is, the type of so-called *artificial-natural*. These trials however all are ongoing, in improving, actually the improving maybe endless as the advancing idea with time seems endless.

Kirkby had warned during 2004 that "There has been a movement away from field work and toward an almost complete dependence on modelling" [37], more than 10 years later, Burt and McDonnell (2015) described how field scientists have posed strong and sometimes

outrageous hypotheses – approaches so needed “in an era of largely model-only research”, “go further and further down the rabbit hole of model uncertainty estimation” [38]. A more unified and holistic theory as called for by Sivapalan [39] is still on the way depending on experimental efforts. Education also needs to be the antecedence, “field work’s primary purpose must be to teach our students to be curious, to look, to collect data, to test existing ideas, to develop new hypotheses, including outrageous ones” [38]. Watershed hydrological experimentation seems in the risk to be marginalization however, “it now is indeed an exciting time for hydrologists/experimentalists to rise up for a new era of scientific hydrology” [9].

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Author details

Jiu-Fu Liu*, Ai-Min Liao, Niu Wang, Jin Lin, Hong-Wei Liu, Wen-Zhong Wang, Tao Ma, Zhao Cai, Min-Han Liao, Xue-Gang Li, Peng Zhuo, Na Yang, Jia-Ju Lu and Wei-Zu Gu

*Address all correspondence to: jfliu@nhri.cn

Department of Hydrology and Water Resources, Nanjing Hydraulic Research Institutes, Ministry of Water Resources, China

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