

Playing with water – An introduction to experimental hydrology

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Abstract

Water is the most important resource for the humankind, thus understanding hydrological processes could be considered a vital task. Therefore, the main aims of this paper are to assess: (i) the current status of hydrologic field experiments; (ii) the techniques and the stages of the field hydrologic experiments at the micro-scale/plot-scale. Microscale hydro-logical studies are important both socially and - economically as they emphasize the role of key factors (e.g. slope) in the utilization of water resources, the identification of critical hydrological thresholds for mobilizing, the propagation of soil particles in water flows and also the time it takes for pesticides, nutrients, and heavy metals to be mobilized. The key to conducting a successful hydrological microscale experiment lies in performing repeated attempts in the field. From an economic point of view, expedition (temporary) hydrologic field experiments are beneficial, as they shorten the working period and reduce the financial costs of the data acquisition process.

One of the challenges of experimental hydrology is the manipulation of "upscaling" or the statistical approach taken towards gathering and processing data.

Keywords: *hydrologic experiment, field, plot scale, runoff*

Rezumat. Experimente cu apă - Introducere în hidrologia experimentală

Apa este cea mai importantă resursă pentru omenire, prin urmare înțelegerea proceselor hidrologice poate fi considerată o sarcină vitală. Astfel, obiectivele principale ale acestei lucrări sunt: (i) stadiul actual al experimentului hidrologic de teren; (ii) tehnicile și etapele experimentului hidrologic de teren la mică scară (scara parcelei). Studiile hidrologice la mică scară sunt importante, atât din punct de vedere social, cât și din punct de vedere economic, deoarece subliniază rolul factorilor condiționali (de ex. panta) în utilizarea resurselor de apă, în bugetul sedimentelor (identificarea pragurilor hidrologice critice pentru mobilizarea și propagarea fluxului de particule de sol) precum și timpul necesar pentru propagarea pesticidelor, a substanțelor nutritive și a metalelor grele. Cheia pentru a efectua un experiment hidrologic de succes la mică scară constă în realizarea de încercări repetate în teren. Din punct de vedere economic, experimentele de teren, expediționare (temporare) sunt benefice, deoarece scurtează perioada de lucru și reduc costurile financiare ale procesului de achiziție a datelor. Una dintre provocările hidrologiei experimentale este manipularea "upscaling" sau abordarea statistică pentru colectarea și prelucrarea datelor.

Cuvinte-cheie: *experiment hidrologic, teren, scara parcelei, scurgere lichidă*

Introduction

An experiment is a scientific concept about a test or a simulation/manipulation for the purpose of discovering something unknown, proving an impact, exploring an effect, or validating a hypothetical principle (Hinkelmann and Kempthorne, 2008).

Experimental research can provide a good basis for understanding the mechanisms of processes (Huang et al., 2015), and for making future predictions (e.g., water budget; erosion rates).

The principle of an experiment involves studying the relationship between independent variables (spatially and temporally represent inputs) and dependent ones (output).

Conducting an experiment may also contribute to answering some qualitative questions and the re-

sults may lead to finding optimized solutions (Dear, 2015). History has recorded many valuable and well known famous experiments, such as those carried out by Archimedes, a Greek physicist, engineer, inventor, and astronomer (showing us that an object immersed in water always displaced a volume of water equal to its own volume); by the English physicist and mathematician Newton (who uncovered the law of universal gravitation, which states that a particle attracts every other particle in the universe using a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them); and by the Russian physiologist Pavlov (the conditioned reflex experiment) etc.

In almost every discipline, science development requires experiments. The main areas of activities which

necessarily require field experiments are biology, chemistry (e.g., cosmetics; pharmacology) and technology in its broadest sense (automotive, robotics etc.). In earth sciences, experiments can be also performed in the following disciplines among others:

- ecology: chemical transport (urea) in unsaturated soils; nutrients (Neagoe et al., 2014; Păun et al., 2015);
- geomorphology (Huang et al., 2015; Cantón et al., 2018);
- environmental science and physical geography (Benavides-Solorio and MacDonald, 2001);
- pedology (Mircea et al., 2015; Laufer et al., 2016);
- agronomy (Dincă et al., 2012);
- hydrology (Stanciu and Zlate, 1988; Gu et al., 2013).

A hydrologic experiment is a complex process, as it intentionally imposes a treatment on a sample plot, resulting in the collection of hydrometric data, which must be subject to rigorous analysis for validation (Ma et al., 2017).

Due to their complexity, experimental field studies require a broad spectrum of knowledge from different disciplines, such as hydrology, pedology, phytology etc. (Song et al., 2015). Hydrological experiments can be performed in the laboratory (short term) or, most often, in the field with two working regimes: stationary (quasi-permanent), or expeditionary (temporary) (Wescoat, 2017).

From an economic point of view, the cost of maintaining experimental or representative hydrological stations involves high financial efforts and time-consuming. Often, due to economic issues, some hydro-meteorological activities are being reduced, and one of the most pressing is the closure of the experimental basins (EBs) (Toebe and Ouryvaev, 1970).

For example, in Russia, after 50 years, the Kolyma Water-Balance Station (1948), a unique scientific research hydrological and permafrost catchment EB, was closed in 1997 (Makarieva et al., 2018). Also, in Romania, the number of representative basins in 2018 was reduced to 14, compared to 40, as they existed in the 1980 (Blidaru, 1980). A fortunate exception is the most long-lived and fully equipped EB with a focus on hydrological research in Romania, namely the Voinești Experimental Basin – the former Station for the Experimental Hydrology of Voinești – which started around 1964 (Minea et al., 2018).

Plot-scale experimental studies are designed to understand interrelationships between processes involving hydrological, ecological, and geomorphological factors (Sheng, 1990; Linsley, 2009). In this respect, Boix-Fayos et al. (2006), with regards to issues pertaining to soil erosion, and field plot experiments have identified and analyzed several "restrictive" factors regarding the suitability and performance of a field experimental design e.g.:

- temporal and spatial scales of measurements,
- the representation and disturbance of natural conditions,
- the complexity of ecosystem interactions.

In fact, there is no standard methodology regarding the study of hydrological processes by means of field experiments (infiltration, runoff, and erosion rates), but there are a big number of examples of good practices, such as Toebe and Ouryvaev (1970); Hudson (1993); Humphry et al. (2002). The current hydrometric technique evolved so that changes in time resolution and new measurements emerged (e.g., the ability of water level sensors to obtain and store a precise data).

Therefore, in this paper, we seek to assess: (i) the current status of hydrologic field experiments; (ii) techniques and phases of the field hydrological experiments at plot-scale. We also discuss a number of "raised issues" (such as plot scale size, synthesis or a regionalized perspective) in the research literature and field experiments.

Research method

A great deal of hydrologic experimental work involves understanding the experimental setup. Based on the literature review background and personal field observations and experiments (setup or design) we depicted the most important steps to be followed in hydrologic field experiments.

The main scientific method consisted in literature screening of a number of references found in scientific databases such as Scopus and ISI of Web Science. The methodological approach of this paper is based on literature interpretative (office) and exploratory (field) activities.

The literature review in experimental hydrology is one of the research branches of the hydrological sciences and represents the basis for studies of observation, understanding, and prediction of water resources processes (Rui et al., 2013). The element that stands out is the experiment itself.

Hydrologic experiments might be classified according to different criteria, such as domain, scale (size); place (in the laboratory and/or on the field).

Field experimental hydrology

A field hydrologic experiment should facilitate the testing of several hypotheses – an analysis of a rainfall event that can be tested by experimentation – and allow for identifying solutions and for making predictions), (Fig. 1).

The overriding principle for experimental design (a runoff plot up to a block of runoff plots) is to keep the setup as simple as possible (Kinnel, 2016).



Figure 1: Experimental aspects with micro-portable rainfall simulators were set up in the field to simulate rainfall events on plots receiving runoff, suspended load, and sheep manure (Aldeni hillslopes, 2017, Source: G. MINEA)

For a microscale experiment, the researcher should use independent variables (e.g., rainfall intensities, soil moisture; nutrients concentration), in order to observe the effects on the dependent variables and establish the causal relationship between variables (e.g., precipitation-runoff) (Bagarello et al., 2014; Prima et al., 2018). Sheng (1990) claims that standardization of plot design and management practices should be considered in order to avoid mistakes. In order to be valid, a hydrologic experiment must essentially have the following three characteristics (Blume et al., 2017):

- Be representative;
- Allow for duplication (manipulation/control; comparison of different measures);
- Be adequate for undergoing a statistical treatment (e.g., linear regressions, ANOVA).

The control refers to the use of control group and controlling the effects of extraneous variables on the dependent variable in which researcher is interested.

Hydrologic scale area

The hydrologic scale area can be distinguished into different groups such as microscale (1 sq cm → 1 sq km - simulation of elementary hydrological processes), mesoscale (1 sq km → 1 Mio sq km - Continents), and macroscale (1 Mio sq km → Global), (Figure 2). The problem of the scales has been considered a crucial topic among the hydrological scientific community (Dooge, 2013). The size of

experimental plots can vary depending on the goal of each research:

- micro-plots (1 sq cm up to one or two square meters, known as monolith);
- small-scale (e.g. ~100 sq m);
- hillslopes/field plots (e.g., 1 ha up to 1 sq km) (Becker and Nemec, 1987; Hudson, 1993).

Blöschl and Sivapalan (1995) considered that small length scales are associated with small time-scales or hydrological processes at the pedon scale. Also, other significant lengths and time scales for hydrology process sizes (e.g., the experimental plot: 10 m length and 10 s time) were elaborated by Dooge (1986). Hydrologic microscale area can vary from plot to the basin (small catchment):

- **Microplot** (used for studying runoff-infiltration, erosion, etc.). For example, Kidron (2007) analyzed runoff yield for measuring over crusted (i.e., surfaces covered by 1–3 mm of cyanobacterial crust) and scalped 3.6–6.3 sq m plots at the Hallamish dune field (Negev Desert, Israel); also, Sui et al. (2016) used treatments of control and micro-basins with block space of 65 cm, 75 cm, and 85 cm. Malvar et al. (2008) selected various monitored runoff and erosion following wildfires on bounded plots of the same dimensions as the plots (0.28 sq m). It is also remarkable that Seitz et al. (2016) determined sediment delivery and runoff volume using micro-scale runoff plots (0.4 m x 0.4 m);

- **Plots**, commonly used for studying runoff, infiltration, snowmelt, erosion, and sediment production processes); pan evaporationimeter (Stan et al, 2016) or for installing lysimeters (Matušek et al., 2016);

- **Basin** or - Experimental Basins (EBs): it uses to serve primarily a research tool and represents the best facility for teaching practices of collection, handling, and analysis of hydrometrical data (UN-ESCO, 1983). From a hydrological point of view, EBs are typically natural laboratories, which play an important role in understanding the dynamics of genetic (natural or simulated rainfall) and key (soil, land use, vegetation type, anthropogenic activities, etc.) factors that influence the overland flow, suspended sediment discharge (Minea and Moroşanu, 2014; 2016) and connectivity processes (Keesstra et al., 2018). A typical example of the experimental hydrographic basin is the Valdai Scientific-Research Hydrological Laboratory, also named Valdai Branch of the State Hydrological Institute (SHI), Russia - established in the 1930's (Uryvaev, 1953, quoted in Gu et al., 2013).

In Romania, experimental research designs have been set up in several geographical regions in particular to study the dynamics of soil erosion under a variety of land-uses. The opening of experimental centers/basins (e.g., Cean, Perieni, Podu-Iloaiei, Aldeni) during the 5–6th decades of the twentieth

century created favorable conditions for more in-depth studies, which provided an important insight into the succession of agents-processes-forms, allowing the first empiric quantitative evaluations on landslide morphodynamics (Rădoane and Vespremeanu-Stroe, 2016).

Hydrologic scale time

The relationship between the microscale and temporal process scales in hydrology is founded upon the intensity of various phenomena and the antecedent conditions (Kikuchi et al., 2015).

The most important element that impacts the time scale of a hydrologic experimental study is

determined by the runoff plot characteristics (Skøien et al., 2003), such as the size, shape, and orientation (Bagarello et al., 2013).

The lifetime of runoff plot processes can span from a few seconds (Hortonian flow) to several hours (see Fig. 2). It is safe to affirm that the shortest durations are specific to the field experiments based on "events time" (Fig. 2). There are also longer runoff plot processes, taking up to 24h and which can be found on soil water balance plots for subsurface and base flow (Figure 2). All characteristic space-time scales need to be interpreted with caution (Skøien et al., 2003).

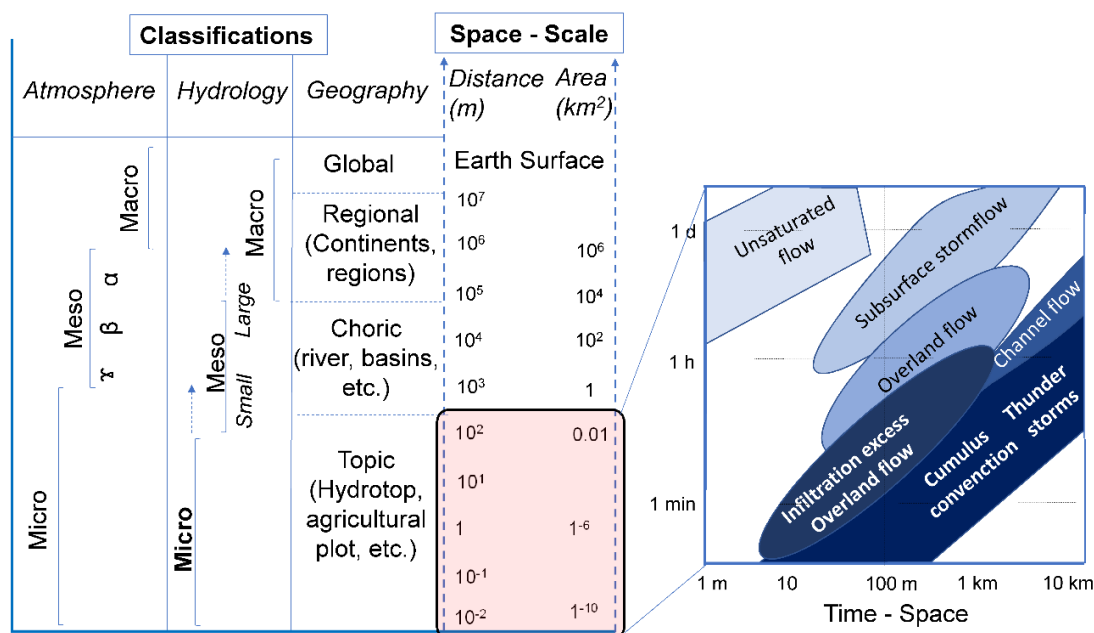


Figure 2: Classification of time-scales and associated activities in hydrology (from Becker and Nemec, 1987) with a focus on minimum time-space characteristic at event scales (from Skøien et al., 2003)

Techniques and steps of the field hydrologic experiment

The scientific way to fulfill every objective of a hydrological study is by doing continuous measurements of variables and field observations.

Also, great attention should be paid to reduce efforts aimed at minimizing the effects of failures during the experiment.

Instrumentations – For the identification of runoff processes at micro-scale, rainfall simulators and micro-simulators may be used (Iserloh et al., 2013). Preferential flow can be followed by dye tracers (e.g., Brilliant Blue FCF) (Pecly and Fernandes, 2017; Stefano et al., 2018). The choice of automatic devices (e.g., water level recorders, sediment samplers) must be made depending on the purpose and the budget of the study (Diyabalanage et al., 2017; Mohammadkhan et al., 2011). Usually, only robust

equipment should be chosen, for which the repairing and maintenance service is readily available (Sheng, 1990). Complementary, manual data collections using simple devices/ techniques are also necessary (e.g., soil probes; sediment samples) (Taguas et al., 2015, 2010).

Measurements – are the main operations and the direct way through which quantitative data are produced (e.g., rainfall depth; discharge series) with regard to the causal effect between independent and dependent variables. Hydrologic data stages concern the collecting and analyzing hydrometric data and the examination of the effect of an independent variable on a dependent variable (Higson and Singer, 2015). A good hydrologic dataset (quantitative and qualitative data series) involved in experimentation allows for results' validation and may be up-scaled and/or generalized by means of ex-

trapolation (Ben Slimane et al., 2015; Merchán et al., 2018).

Observations - are complementary, systematic type of activity consisting of attentively watching and examining phenomena (e.g., time concentration, river bank degradation, etc.). The observer, based on an established protocol, must collect, during the experiment, the information that would highlight any inconsistencies between rainfall, infiltration and flow (e.g., lag time: peak discharge time) (Biddoccu et al., 2016; Evans, 2005).

Hydrometric data are valuable, demanding important capital and human resources (Hamilton, 2012). The quality and seriousness of the observer and/or researcher are the keys to the success of an experiment. Techniques to remember when performing observations:

- field observation sheet should provide supplementary information (notes) regarding atmospheric phenomena, land use changes, morphological landscape evolution etc. (Cerdà et al., 2018).
- field photograph - complements the informational table by capturing important moments in time (e.g., rainfall drop, splash erosion, infiltration time, runoff, and surface storage during a natural or artificial rainfall) as well as documents details about the space and require extensive note taking (Marzen et al., 2015).

Automated (measuring) activities need to be duplicated by systematic observations in order to avoid loss of information (e.g., leakage times, pipe collector does not clog the grass or clump). These observations must be carried out permanently throughout the experimental period (rainfall-runoff, snowmelt-runoff) in order to allow the intervention in accidents in order to prevent damage to installations and the failure of experiments.

Failure of experiments

In the scientific world, it is admitted that "*failure to reproduce results is a normal part of how science works*" (Open Science Collaboration, 2015). Failures of hydrologic experiments are a part of fieldwork. When planning a hydrological experiment, it should be considered that any field experiment is vulnerable. The vulnerability can occur when the analysis of the effect associated with technical and climatic factors does not take into account all the means of prevention, elimination/avoidance. Possible cause of failure during experiments:

- from the technical point of view: it is not possible to have absolute control over extraneous variables (e.g., nozzle clogging of rainfall simulator); instrumental errors (accidental loss of measured data; clogging water tanks and wrecking water levels; mistaken setting of the data logger);
- environmental: field-based exploitation requires knowledge of weather forecasts in order to avoid wind influence through windshield use and the effect

of high temperatures (high evapotranspiration); the impossibility of varied hydrological testing of land plots with various soil properties and with different slopes; or destruction of devices due to animals or insects.

Steps of the field hydrologic experiments

The scientific methodology of hydrologic field experiment involves a series of steps that are used to investigate a natural or simulated event. The independent variable of microscale hydrologic studies is the rainfall or snowmelt event, which makes possible the research of different hydrologic parameters: infiltration rate, runoff discharges or volume, lag time, erosion rate. A protocol should be followed when performing an experimental study (Humphry et al., 2002; Kibet et al., 2014). The stages of the hydrological field experiment are as follows: plot homologation and instrumentation (Fig. 3). Scientific homologating of field plot should consider two criteria: representativity and accessibility (Stroosnijder, 2005).

A runoff plot must be considered representative of a basin if it meets a few criteria (Kavian et al., 2017; Wirtz et al., 2010): it is relatively homogeneous in soil and vegetation and exhibits uniform physical characteristics. Also, the soil use under a plot may be deliberately modified for study purposes, e.g., an hydrohill catchment with 512 square meters of concrete aquiclude (Weizu and Freer, 1995).

Once the research objective has been established (e.g., quantitative identification of intensive grassland erosion), maps and site plans will be analyzed and field-based mapped to identify site variants (Cunha et al., 2017). After finalizing the chosen variant, the topographic elevation of the approved land shall be carried out at a scale of 1: 100 - 1:2000, depending on the size and number of parcels.

The plots, regardless of their number (a runoff plot; a paired-runoff plot; a block runoff plots), will be placed with the large side perpendicular to the level curve, even if it is not parallel to the parcel plot (Boix-Fayos et al., 2006). The cardinal orientation of one of the small sides must be northward. Thus, a pair of parcels may have the shape of a valley according to the shape of the land.

When placing plots, one should also consider:

- the road network accessibility;
- the agreement on land accessibility, regardless of ownership (public/private);
- avoiding the influence of adjacent and unwanted factors (e.g., uses and experiments on adjacent plots, adduction network, evacuation network, cabinets with appliances, etc.).

All adjacent experimental runoff plots will be mapped at the right/adequate scale using conventional signs so as to create a detailed and overall picture of the experimental area/perimeter.

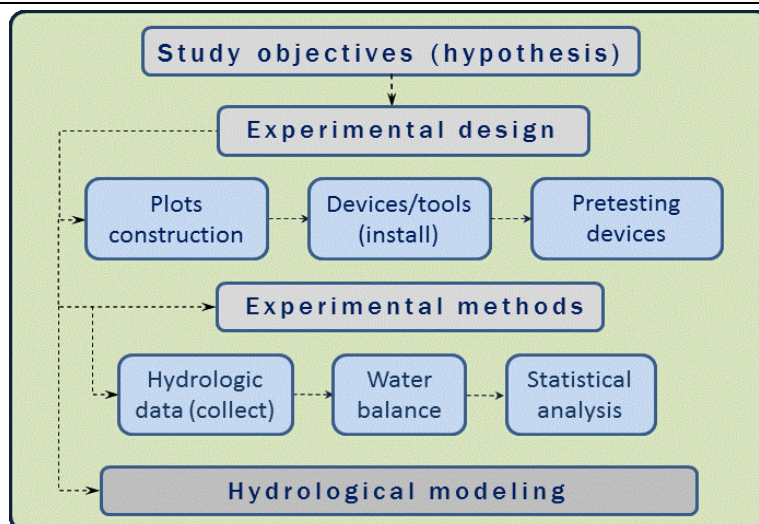


Figure 3: Workflow of the hydrological experiment protocol

Hydrological field experiment protocol

The protocol of a hydrological field experiment for the rainfall-runoff study describes how it will be experimented and should include the following elements (Fig. 3):

a) set a hypothesis - desk documentation - establish-ing the hypothesis and the experimental method (e.g., what is the effect of vegetation on the forma-tion of water resources, how it affects the chemical concentration of the fruit trees, the water in the soil, the anthropogenic perturbation of the hydro-logic cycle); literature review books and papers, topographic and soil vegetation maps, aerial images, guidance and any other sources relevant in relation to the research problem being investigated (perform simulations for products; evaluate, interpret and justify simulation results);

b) establish the experimental protocol:

- choosing the members of the experimental team (observer/technician/hydrologist) and setting work tasks;
- geomorphological condition: slope, aspect, land use; accessibility;
- plot setting (dimensioning; round and rectangular shape; arrangement);
- vegetation study (appearance; cover);
- setup of the necessary equipment for measurements (water level sensor, volumetric water content sensors, label collection bottles) and observations (land plotting guide);
- proper choice, design and/or dimensioning of tools for dealing with extreme situations (e.g., water tanks can be clogged quickly when erosion rates are high);

c) planning of the experiments (establishing the calendar and a minimum and maximum number of experiments with the artificial rainfall installation in relation to the objectives of the research; artificial rain intensity: 0.5 mm/min, 1 mm/min, 2 mm/min);

weather and environment conditions research; consultation of weather forecasts to avoid weather conditions that are unfavorable to the experiment, e.g., intense wind; knowledge of antecedent conditions, e.g., API3, soil moisture);

d) field setup - because the validity and repeatability of an experiment are directly affected by its construction and/or execution, setup and installation of devices, taking great care when creating the experimental design is very important; pretesting available tools/devices (e.g., setup; calibration; control measurement; data tests download);

e) test the hypothesis – for example, performing a rainfall simulation; repeating the experiment will extend the hydrologic series, and minimize the effect of experimental errors and reach a more accurate conclusion;

f) analyze the results (water balance, statistical analysis, hydrologic modeling) and write the outcomes, communicate conclusions respectively.

Challenges and social awareness of hydrological experiment fields

As we above-mentioned, hydrological experiments under filed conditions allow us describing the main water processes and issues at different spatiotemporal scales of the most important natural source for the humankind and ecosystems. However, despite the increasing number of publications and diversity of methods as confirmed several editors of the most important hydrological journals (Quinn et al., 2018), further work is still necessary in order to consider the hydrology as a policy-relevant science (Takeuchi, 2004).

As several authors confirmed, soil erosion (García-Ruiz et al., 2013), water pollution (Liu et al., 2017) or flash floods (Alaoui et al., 2018) among others, do not have clear patterns, origins and control measures and further research must be con-

ducted using hydrological experiments under field conditions.

The use of experiments in hydrology also allows us including an obviated key factor in earth science studies, the human impacts (Lu et al., 2018). Hydrologists and related researchers should pay attention to other disciplines such as geomorphology (Seeger, 2017) or soil science (Rodrigo-Comino et al., 2017) in order to make more consistent their results combining different points of view and increasing the representativity.

Conclusion

In this paper, the manners of obtaining hydrological data at the microscale, as well as the protocols of a hydrological (rainfall-runoff) field experiment were indicated.

Runoff plots are important hydrometric tools for hydrological studies. From an economic point of view, expedition (temporary) hydrological land experiments bring benefits as they shorten the working period and reduce the financial costs of the data acquisition period. The key to a good hydrological experiment at microscale consists of repeated attempts in the field (pretests, carefully designed and maintained) and seriousness.

One of the challenges of experimental hydrology is the manipulation of "upscaling" data (see Cantón et al., 2018) generalized by extrapolation, and statistical approach. Dooge (1986) depicts that "a great contrast between statistical physics and statistical hydrology in regard to the sizes of the aggregates involved and, in the fact, that the hydrological phenomena of major interest involve transient rather than equilibrium behavior."

However, from event scales of minutes to hours at microscales, quantifying extreme rainfall rates remains a challenge.

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