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LABORATORY STUDY OF WATERSHED HYDROLOGY

A Contribution to the International Hydrological Decade

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Department of Civil Engineering
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SYNOPSIS

Conventional approach to study the rainfall-runoff relationship of a watershed uses historical hydrologic data to fit a black-box model for simulation of watershed hydrologic behavior. A host of measurements of rainfall input and runoff output from watersheds are available but there is as yet no general theory to explain the course of mechanics of flow from input to output. The proposed laboratory approach aims to investigate the basic laws and principles controlling the mechanics of runoff from the watershed. It employs a watershed experimentation system (WES) as a tool for the research. The WES is a system of instrumentation of integrated hydraulic, electronic and structural design. It can produce an artificial rainfall of variable time and space distribution to move over a laboratory area of 40 ft. by 40 ft. or less, thus capable of simulating a storm moving in any direction over a testing drainage basin constructed within the area. The experiment is controlled electronically by a digital computer and the output runoff measured by sonar detectors for transmitting information to the computer for immediate recording and analysis. Various problems being studied include the time factor in runoff process, the conceptual watershed roughness and the effect of storm movement on peak discharges. The WES may also be used to study subsurface runoff by employing testing basins made of porous material, thus considering an additional depth dimension of the runoff process. However, it is not the immediate objective to study watershed modeling before the basic dimensionless flow criteria become known.

SYNOPSIS

La démarche conventionnelle suivie pour étudier la relation pluie-ruissellement d'un bassin utilise les données hydrologiques historiques que l'on adapte à un modèle-boite noire simulant le comportement hydrologique du bassin. On dispose d'une foule de mesures de l'apport de pluie et de la production de ruissellement de bassins mais jusqu'à présent il n'existe pas de théorie générale qui permette d'expliquer la mécanique de l'écoulement entre l'apport et la production. L'approche en laboratoire proposée a pour but d'étudier les lois et principes de base qui contrôlent la mécanique du ruissellement d'un bassin. Elle utilise un système expérimental de bassins (WES) comme instrument de recherche. Le WES est un système instrumental de conceptions hydraulique, électronique et structurale intégrées. Il peut produire une pluie artificielle à distributions temporelle et spatiale variables, se déplaçant sur une surface de laboratoire de 40 pieds sur 40, ou moindre, capable donc de simuler un orage se déplaçant dans une direction quelconque sur un bassin de drainage expérimental construit sur cette surface. L'expérience est contrôlée électroniquement par une calculatrice électronique et le ruissellement produit est mesuré par des detecteurs sonars envoyant l'information à la calculatrice qui l'enregistre et l'analyse sur le champ. Parmi les différents problèmes traités citons le facteur de temps du phénomène de ruissellement, la rugosité théorique du bassin et l'effet du mouvement de l'orage surles décharges de pointe. On peut également utiliser le WES pour étudier le ruissellement souterrain en utilisant des bassins expérimentaux en matériaux poreux, ajoutant donc une dimension en profondeur au phénomène de ruissellement. Cependant, nous n'avons pas pour objectif immédiat d'étudier la manière de façonner des bassins avant de connaître les nombres de base sans dimension caracterisant l'écoulement.

INTRODUCTION

One important problem in watershed hydrology is to understand the relationship between the input rainfall and the output runoff of a watershed. The conventional approach to investigating this problem is generally characterized by two basic features: the use of natural hydrologic data and the simulation by means of a lumped-system model.

Quantitative scientific data may be classified into two kinds: experimental data and historical data. The experimental data are measured by experimentation and usually can be obtained repeatedly by experiments. The historical data, on the other hand, are collected from natural phenomena that can be measured but observed only once and then will not occur again. Natural hydrologic data, such as rainfall and runoff, are historical data which were observed from natural hydrologic phenomena.

The relationship between rainfall and runoff is a very complicated phenomenon influenced by numerous climatic and physiographic factors. Undoubtedly, these factors are also interrelated and interdependent among themselves. Because natural rainfall and runoff data are historical data, it is impossible to reproduce them with only one or few factors varying at each time in order to determine the sole influence of the one or few factors upon the rainfall-runoff relationship. Using the natural data, only empirical and statistical relationships can be derived but the basic laws or principles played by a certain influencing factor cannot be readily determined. For example, the effect of the direction of movement of storms upon the peak discharge cannot be validly investigated by conventional approaches because it is impossible to request a historical storm to occur again in various directions over the same watershed under the same hydrologic conditions.

Simulation of natural phenomena may be achieved by means of either a lumped-system model or a distributed-system model. When a phenomenon is simulated by a lumped-system model, it is treated as a "black box." A gross representation of the black box is determined from the input and output data pertaining to the box but no interest or concern can be given to the process going on inside the box. In such models, position is not important and all components of the system being simulated are regarded as being located at a single point in space. On the other hand, if the internal process of the model is analysed, the system is not regarded as being considered at a single point in space but various distributed points or areas within the internal space of the system must be simulated, thus constituting a distributed-system model.

Simulation of rainfall and runoff relationships by conventional approach can be exemplified by the use of a unit hydrograph, which is essentially a black box determined deterministically or statistically from historical rainfall and discharge data. Mathematical formulations of the unit hydrograph and other linear and nonlinear black-box models have also been developed in recent years. However, all such methods are lumped systems in nature. The fundamental principles involved in the methods have not been extensively investigated theoretically or experimentally as far as the internal process of the black box is concerned. In other words, the use of such lumped-system models does not explain the basic mechanics of flow through the watershed because it is only a simulation of the black box as a whole and offers in effect merely a mechanical aid to data fitting. For example, the term "time of concentration," frequently used in the rational method of peak discharge determination, has been theoretically defined as the time required for a particle of water to travel from the remotest point on the drainage basin to the outlet of the watershed, but no one has accurately traced this water particle over the space of the watershed in order to determine the physical laws that control this time. The time of concentration used in the conventional method is generally calculated only very approximately from some empirical formulas derived statistically from the natural hydrologic data.

In general, a host of measurements on rainfall input and runoff output from drainage basins are available for the study of watershed hydrology, but there is as yet no general theory to explain the course of mechanics of flow of water from input to output.

CONTROLLED LABORATORY EXPERIMENTATION

In view of the weaknesses of the conventional approaches to watershed hydrologic studies as described above, it is proposed to employ controlled laboratory experimentation for the investigation of the basic laws governing the flow of water over drainage basins. For the surface runoff over drainage basins, two phases of runoff can be recognized; namely, the overland phase and the open-channel phase. The hydraulics of open-channel flow have been extensively developed. Many hydraulic studies of overland flow have also been made in recent years, but consideration was taken only for flow over a narrow strip of the plane surface and the momentum effect due to spatial rainfall input has been mostly ignored. The flow over a drainage basin is composed of overland flow intermingled with open-channel flow. For the study of watershed hydrology, it is necessary to investigate the integrated phenomenon of overland and open-channel flow. The hydraulics of this approach may be called the <u>watershed hydraulics</u> as distinguished from the well-developed open-channel hydraulics and the hydraulics of overland flow. The watershed hydraulics considers the combined hydraulic behavior of overland and open-channel flows. As little study has been made in this effort, the watershed hydraulics may open up a new area of study for the benefit of understanding the watershed hydrology.

Owing to the complex nature of the flow over drainage basins, the development of watershed hydraulics may take many years. As a step toward this development, it is proposed to construct laboratory drainage basins of geometric shapes and artificial roughness so that the basin characteristics can be subjected to more exact theoretical analysis and to more accurate experimental observation than those applicable to natural watersheds. In addition to the shape and roughness of the drainage basin, other characteristics for experimentation may include slope, size, basin storage, channel pattern, and many other physical variables. The input to the laboratory drainage basin is introduced as artificially controlled storms of variable temporal and spatial distribution. The artificial storms can be created by electronically operated raindrop producers so that different patterns of rainfall supply and even the movement of storms can be produced effectively.

By varying rainfall input and basin characteristics, different flow behavior over the drainage basin and the outflow hydrographs are recorded. The information so obtained will be the experimental data for numerous combinations of physical factors. Such information is otherwise unobtainable in the case of natural hydrologic data. Since all variables involved in the experiments are rigidly controlled, the phenomenon of flow over the drainage basin can be analyzed readily by basic hydrodynamic principles. The analytical results thus obtained can be checked against the experimental observation. Due to the large number of variables and complicated mathematical formulations that may be involved in the proposed approach of study, the operation of the experiments and the theoretical computations must be properly programmed and performed on high-speed electronic computers.

WATERSHED EXPERIMENTATION SYSTEM

A system of instrumentation for the experimental investigation of the rainfall-runoff relationship has been developed, designed and constructed at the Hydraulic Engineering Laboratory of the Department of Civil Engineering, University of Illinois. This system as shown diagrammatically in Figure 1 provides an invaluable tool for the proposed approach of study of watershed hydrology.

The <u>watershed experimentation system</u> (WES) can generate an artificial storm of given time and space distributions of rainfall intensity over an area of 40 feet by 40 feet. Within this area, a testing drainage basin can be built and its area, shape, slope, surface roughness and storage capacity can be altered. The entire system of instrumentation consists essentially of four parts: input assembly, receiving assembly, output assembly, and process control assembly.

The input assembly consists of a hydraulic head system to provide the required flow of water at a constant pressure, a water distribution system to produce raindrops of various intensities changing with time and space, and a structural framework to support these systems. The hydraulic head system supplies a range of flow from 0.53 gpm to 133 gpm from a pump which feeds the water distribution system under a constant head corresponding to 12 lb/sq.in. for varying flow rates to generate storms of rainfall intensity ranging from 0 to greater than 8.00 in. per hr. over basin areas ranging in size from ~~100~~ 16 to 1600 sq. ft. In order to produce this range of flow, the system consists of two branches, one for low-flow range of 0.53 gpm to 13.3 gpm and the other for high-flow range of 8.28 gpm to 133 gpm. The water distribution system contains 100 digital valve assemblies, each regulating flow, at 16 different rates, to four raindrop producers so that 16 different rainfall intensities within the available range can be obtained. The raindrop producers[1] as shown in Figure 2 are hollow boxes made of 3/8-in. plexiglas, having outside dimensions of 2-ft. by 2-ft. by 1-3/4-in. The bottom square sides of the boxes are each installed at 1-in. centers with 576 polyethylene tubes of 0.023 in. inside diameter and 3/8 in. long. Thus, a total of 230,400 raindrops can be produced by 400 raindrop producers to cover the maximum drainage basin area of 1600 sq. ft. The size of the raindrops can vary with the size of the polyethylene tubes. For the installed size, the raindrops so produced have an average diameter of 3.46 mm which is approximately the average size of most raindrops occurring in natural storms.

The receiving assembly, consisting of a slope control unit and modular basin panels, is to represent the physiographic features of a laboratory drainage basin. The significant features, such as the slope, shape, size, storage capacity, and surface roughness of the basin can be changed in accordance with desired experimental conditions. The slope control unit is designed to pivot the entire testing basin through a longitudinal slope range of 0 to 6.0 per cent by means of six screw jacks. Cross-slope variation is also provided by blocks so that up to 2 per cent cross slopes can be obtained. Portable guide vanes can be installed on the basin surface to guide the flow along the cross-slope direction to the main longitudinal slope, thereby creating two basic slope features in watersheds; namely, the channel slope and the overland slope.

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1. Chow, V. T., and Harbaugh, T. E.: "Raindrop Production for Laboratory Watershed Experimentation," Journal of Geophysical Research, Vol. 70, December 15, 1965, pp. 6111-6119.

If desired, however, any basin topography can be produced by using molding plastics or other suitable material.

The output assembly consists of an outflow tank, 40'0" long by 3'10" deep by 1'7" wide, to collect runoff from the basin and the two sonar depth detectors to sense the water level in the tank and immediately transmit the information to the process control assembly. By means of volumetric calibration of the outflow tank and by controlled recording on time intervals by depth detectors, the outflow discharge can be computed automatically in the process control assembly through comparison with recording of the total outflow as measured by a turbine flow meter placed in the line leading from the pump to the distribution system.

The process control assembly consists of interface and logic circuits, power units, a scanner, hydraulic controls, and a solid state computer PDS-1020 with 4096 words of memory. This process control equipment, called Direct Digital Control (DDC) System is used to control time and space distributions of raindrops in order to produce a given storm pattern for a particular experiment. The given storm pattern is introduced to the system by preprogramming on punched tapes or from an IBM typewriter so that 100 digital valve assemblies are controlled independently for their settings at various times throughout the period of experiment according to the given storm pattern. All 100 digital valve assemblies can be set from a position of fully closed to fully open within 30 seconds. Thus, the computer provides a means of converting individual storm pattern into a repeatable sequential control program, simulating the passage of a rainstorm over the testing basin. The scanner, controllable from the PDS-1020, is used to address each solenoid valve in the digital valve assembly and transfer the current setting to the valve positioning mechanism. The hydraulic controls are provided to perform various important functions such as pressure transmission, low-flow and high-flow selection, bleeder valve control, and safety switch control.

PROPOSED PROBLEMS FOR STUDY

With the availability of the WES as a research tool, a number of studies on the rainfall-runoff relationship have been made, including studies of the time distribution of the runoff process,[2] the conceptual watershed roughness,[3] and the effect of the storm movement. In the study of the time distribution of the runoff process, use was made of a conceptual watershed which is treated as a quasi-linear distributed dynamic system and thereby defined mathematically by a set of quasi-linear partial differential equations for flow continuity and momentum. The conceptual watershed is composed of sloping overland flow spatially feeding a sloping main channel. Various geometric shapes and two main channel slopes of the watershed and different rainfall intensities were employed in the investigation. The analytical results obtained from the conceptual watersheds were tested in the watershed experimentation system. In the same study, a conceptual watershed roughness was introduced and its response behavior to the depth of flow and raindrop impact was disclosed. For the study of the storm movement, a theory proposed by Maksimov[4] was investigated experimentally on the WES.

There are numerous other problems that can be studied systematically using the WES. The study on the effect of input and basin variables upon

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2. Harbaugh, T. E.: "Time Distribution of Runoff from Watersheds," Ph.D. Thesis, University of Illinois, Urbana, Illinois, U.S.A., 1966.

3. Harbaugh, T. E., and Chow, V. T.: "A Study of Conceptual Watershed Roughness," paper to be presented at the XIIth IAHR Congress, Ft. Collins, Colo., U.S.A., 11-14 September 1967.

4. Maksimov, V. A., "Computing Runoff Produced by a Heavy Rainstorm with a Moving Center," Soviet Hydrology: Selected Papers, Am. Geophys. Union, No. 5, 1964, pp. 510-513.

discharge output can be continued and extended. The geometric basins now under investigation are of rectangular, triangular, and circular shapes because such shapes are readily amenable to mathematical and hydrodynamic analyses. Uniform rainfall intensities are first applied to these basins, and the experimental results may be used to verify the analytical solutions. By this investigation, it would be possible to determine the effect of basin shape and to establish a sound basin-shape index for basic classification of watershed shapes.

The uniform rainfall intensities may be later changed to rainfall intensities of nonuniform time distribution, three basic patterns respectively of advanced, average, and delayed types will be tested. For nonuniform space distribution, bands of given rainfall intensities will be programmed and produced to move downstream, upstream, and transversely across the basins. By combining various time and space distributions, complicated storm patterns can be developed and experimented. Thus, the effect of time and space distribution of rainfall and the effect of storm movement on runoff can be further critically examined and analyzed.

The laboratory basins will be constructed for surface roughenss of various kinds and for storage capacity simulating different channel densities and reservoirs. The basin under experimentation is made of masonite board but will be roughened with various roughness elements or covered with fibre-glass, synthetic grass, and other suitable material.

The proposed method of investigation will have immediate value in obtaining new knowledge in urban hydrology. The study of the time distribution in the runoff process can be used to clarify the hypothetical concept of the time of concentration. The widely used rational formula for designing urban drainage system can be critically examined in the light of the experimental findings and new formulas or methods may be developed.

The concept of linearity which constitutes the unit hydrograph theory and its linear mathematical models can be easily examined from the results obtained by this research. Nonlinear mathematical models and concepts can also be tested experimentally.

In recent years, new field evidence is accumulating which leads to the belief that runoff usually originates from a small, but relatively consistent, part of the watershed. The proposed research will make possible the investigation of this pehnomenon by applying a programmed storm of limited size over the so-called "runoff-producing area" of the watershed; thereby, testing the "source-area" concept which is now subject to controversial discussion. The knowledge so obtained would be of immense value to economical planning of soil control programs and to efficient design of flood control projects.

For the study of the mechanics of subsurface flow, the artificial drainage basin may be built with perforated bottom and paved with spongy material. Thus, subsurface flow can be developed, tested, and analysed by the watershed experimentation system. Therefore, the proposed approach of study is not only for surface flow but also for subsurface flow, thus considering the additional depth dimension of the runoff problem.

The work by Mamisao,[5] Chery,[6] and Grace and Eagleson[7] involved watershed stimulation and modeling. The first two authors dealt with modeling of a

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5. Mamisao, J. P.: "Development of an Agricultural Watershed by Similitude," M.S. Thesis, Department of Agriculture, Iowa State College, Ames, Iowa, U.S.A., 1952.

6. Chery, D. L.: "Design and Tests of a Physical Watershed Model," Journal of Hydrology, Vol. IV, No. 3, 1966, pp. 224-235.

7. Grace, R. A., and Eagleson, P. S.: "The Modeling of Overland Flow," Water Resources Research, Vol. 2, No. 3, 1966, pp. 393-403.

given watershed by experiment. Grace and Eagleson analysed the general case of watershed modeling. According to their analysis, use of small-scale artificial drainage basins for study of the rainfall-runoff process in the laboratory is desirable particularly when the process is too complex for accurate formulation of the mathematical equations governing the phenomenon. Thereby, they derived mathematical criteria to define the conditions that modeling of the surface runoff process may be legitimately pursued. However, it is not the immediate objective at the University of Illinois research program to attempt such watershed modeling. A number of dimensionless criteria for watershed modeling must be first developed before such modeling attempts can be made meaningful. The present program is to investigate the basic laws and fundamental principles controlling the rainfall and runoff process. It is hoped that such findings may eventually lead to the discovery of the required modeling criteria.

The investigation of watershed geomorphology is another broad, interesting and important subject that can be investigated by the WES. For future investigation, for example, the model drainage basin may be paved with a layer of fine sand and then exposed to sequentially programmed storms for some time. Eventually, a channel drainage system will be developed and it can be analysed and used to verify many empirical theories that have been proposed in river geomorphology.

ACKNOWLEDGMENTS

The development of the WES and the research program involved was supported by a National Science Foundation grant GP-1464. Continuing research is being supported by another NSF grant GK-1155.

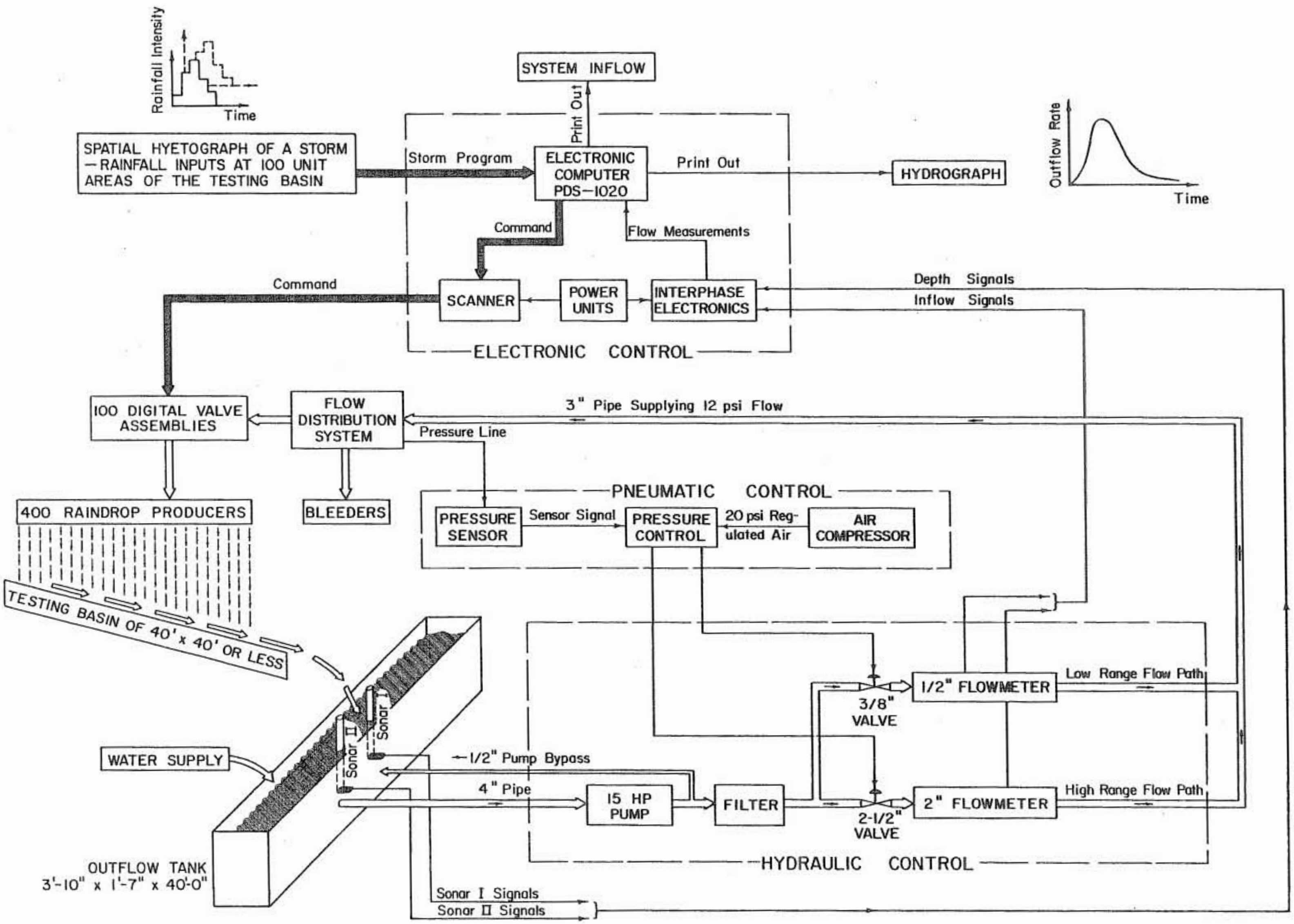

FIG. 1. UNIVERSITY OF ILLINOIS WATERSHED EXPERIMENTATION SYSTEM

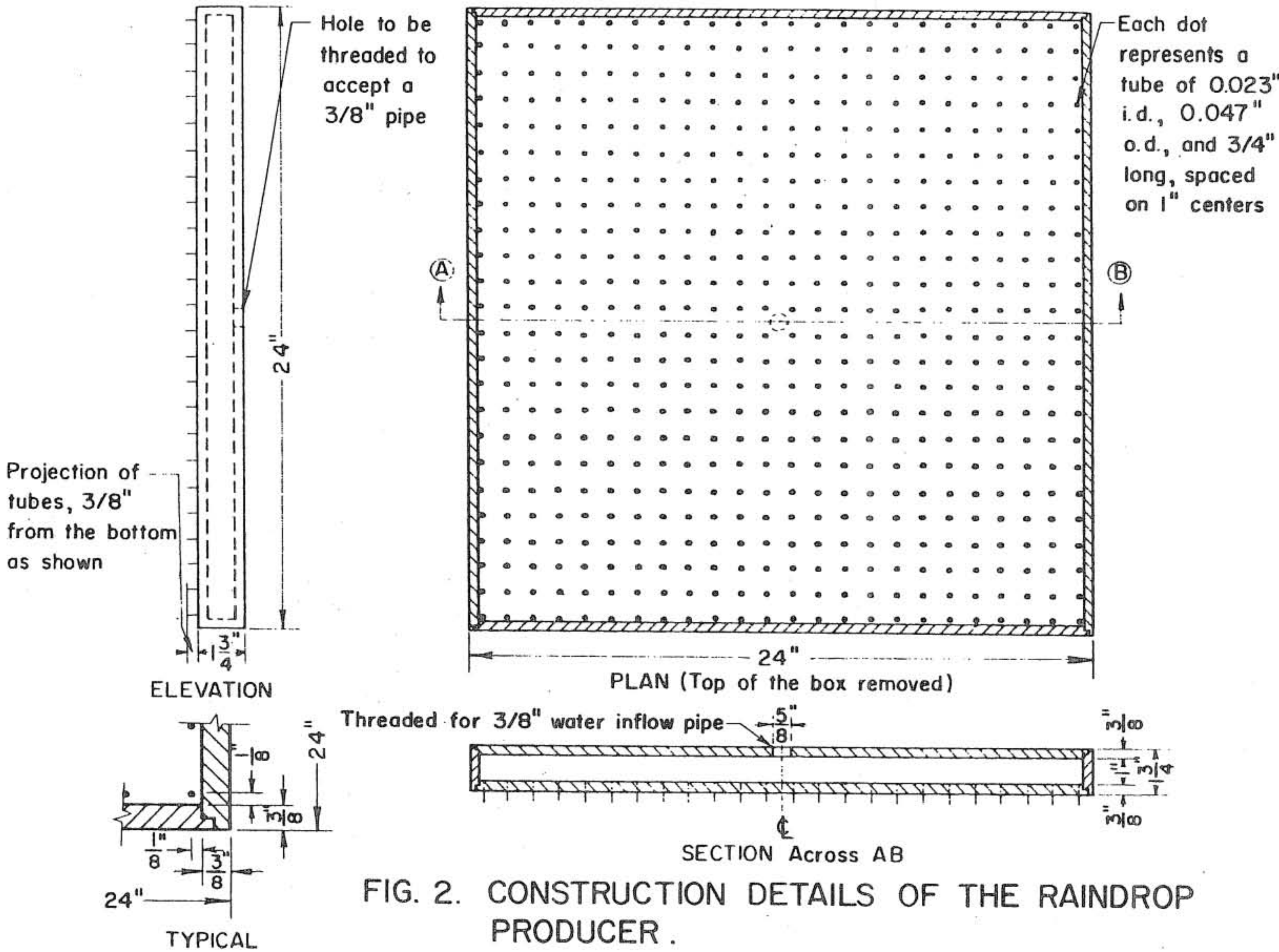

FIG. 2. CONSTRUCTION DETAILS OF THE RAINDROP PRODUCER.

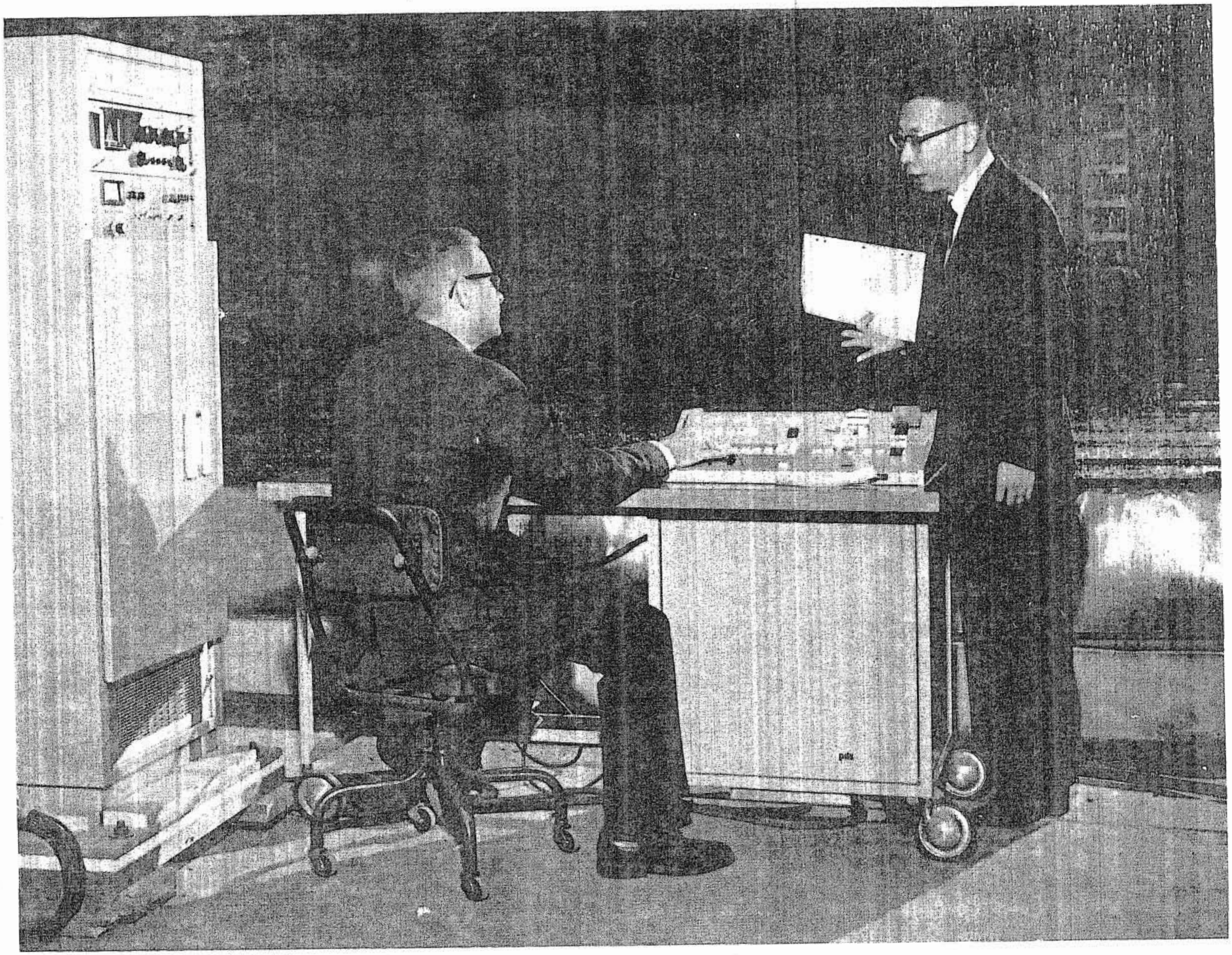

FIG. 3. OPERATION OF THE WATERSHED EXPERIMENTATION SYSTEM