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DESIGN AND TESTS OF A PHYSICAL WATERSHED MODEL*

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Abstract: Theoretical considerations are discussed, and design criteria and fabrication of a physical hydrologic model including a storm-simulating device are described. Data from several preliminary experimental tests indicate that the use of physical models of actual watersheds merits further investigation.

Introduction

Within the past few years, the use of similitude and physical models has been proposed to augment field studies of rainfall-runoff relations. A study to investigate the feasibility of the physical hydrologic model as a research tool was initiated in 1960 by the Agricultural Research Service, in cooperation with Utah State University. The study objective involved the construction and testing of what was designed to be a physical hydrologic model of a small watershed.

The term "physical hydrologic model" has been used to designate an apparatus consisting of two main components – a device to simulate a rainstorm and a scaled catchment area beneath the storm-simulating device. Such an apparatus may be a device applying a simulated uniform and constant rainfall to a simple catchment such as a small field test plot or an intricate rainstorm simulator discharging on catchment areas ranging from simple shapes to models of actual watersheds. The study being reported employed a complex apparatus in the latter category.

Model design

Discharge from a watershed is governed by a complicated interaction of many variables, and there is no *a priori* knowledge of the complete set of variables relevant to the system. Thus, empirical experience and successful theorizing are needed to delineate the pertinent variables. From just such

* Contribution of the Soil and Water Conservation Research Division, Agricultural Research Service, USDA, in cooperation with Utah State University, Logan, Utah.

considerations, the variables expressed in Eq. (1) were assessed as relevant to the hydrologic phenomena that were to be modeled:

$$f(q, t, I, i, r, x_1, x_2, x_3, \mu, \rho, g) = 0 \tag{1}$$

in which

q = outflow rate (per unit catchment area)	LT^{-1}
t = time	T
I = application rate per unit area	LT^{-1}
i = flow abstraction rate per unit area	LT^{-1}
r = "resistance" to flow in system	--
x_1, x_2, x_3 = space coordinates of the points of the watershed surface	L
μ = dynamic viscosity of the liquid in the system	$ML^{-1}T^{-1}$
ρ = density of the liquid in the system	ML^{-3}
g = acceleration due to gravity	LT^{-2}

In determining the relevant variables, certain limitations and assumptions were also involved. They were:

1. The outflow at the basin outlet was derived entirely from surface runoff.
2. The source of the runoff was a rainstorm, more particularly, high intensity thunderstorms (precipitation in the form of snow was not considered).
3. The topographical model would be initially constructed with an impervious surface allowing for no losses through the surface of the model.
4. The designed rainstorm simulator would be an adequate representation of the prototype rainstorm phenomena.
5. The topographic model would be an undistorted, faithful representation of the prototype geometry.
6. The rainfall momentum flux and impinging angle could be combined with the "resistance" term.
7. From the perspective of the prototype, the surface tension of water could be neglected as a relevant variable, but in the model its influence could be included in the "resistance" term.
8. The influence of sediment transportation on prototype performance was insignificant.
9. A portion of the surface storage on the watershed surface could be considered as an element of the "resistance."

As a consequence of the limitations and the unexpressed dimensions of the "resistance" term, Eq. (1) could not be considered complete. Nevertheless, it was considered an adequate expression of the variables involved in the system under investigation, and it was used as the basis for what was called a "quasi" dimensional analysis. The Buckingham Pi Theorem was used to transform Eq. (1) into a functional relation of eight dimensionless terms as expressed in Eq. (2):

$$\begin{array}{c} \qquad \pi_1 \quad \pi_2 \quad \pi_3 \quad \pi_4 \quad \pi_5 \quad \pi_6 \quad \pi_7 \quad \pi_8 \\ f\left(\frac{qt}{x_1}, \frac{It}{x_1}, \frac{\mu t}{\rho x_1^2}, \frac{it}{x_1}, \frac{x_2}{x_1}, \frac{x_3}{x_1}, \frac{gt^2}{x_1}, r\right) = 0. \end{array} \tag{2}$$

Since the discharge at the basin outlet was the desired dependent variable, the Pi term containing this variable was separated from the other Pi terms and expressed as a function of the remaining Pi terms. Then if the contemplated model were to have been a true model, it would have had to maintain the ratio:

$$\frac{\left(\frac{qt}{x_1}\right)_{\text{prototype}}}{\left(\frac{qt}{x_1}\right)_{\text{model}}} = \frac{f\,(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8)_p}{f\,(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8)_m} \tag{3}$$

which would have required the pairwise equality between the π_2 through π_8 terms. This situation was immediately recognized as a physical impossibility. Consequently, judicious decisions had to be made as to where distortions would be permitted by not maintaining the strict pairwise equality.

It followed, from the supposition that the topographic model would be a faithful representation of the prototype geometry, that the model-prototype equality of the fifth and sixth Pi terms should be satisfied. From like reasoning, the assumption of an adequate rainstorm simulator provided for model-prototype equality of the second Pi term. In the initial design and construction, the surface of the topographic model was to be impervious and thus no provision was made for abstraction of flow through the model surface. Further, there was no accurate method of determining the amount of input which would go into permanent storage on the surface of the model. So, with the assumption that the volumetric distortion of the outflow would not unduly affect the time relationships in the performance of the model, provision for model-prototype equality of the π_4 term was neglected for the time being. Thus this term became one of the distortions which would have to be eventually manipulated to establish verification of the model. The same consideration was given to the undefined "resistance" term (π_8). As hypothesized, many items (e.g. surface roughness, rainfall momentum, the temporary storage, etc.) were included in the general resistance term. Again, it would have been impossible to know the proper equality of this term between the model and prototype. Further, it was speculated that proper manipulation of liquid physical properties, model surface-liquid interaction, and model surface textural characteristics would allow for a simulation of the net effect of the many prototype resistances to the flow.

There then remained the two Pi terms, π_3 and π_7, to be considered. It would have been impossible to simultaneously satisfy the model-prototype equality of these two terms. Thus, for construction and initial operation of the model, the hypothesis was made that the gravity parameter (π_7) expressed the dominating influence, and the design was made according to the equivalence of this Pi term between the model and prototype. The "Development of an Agricultural Watershed by Similitude" endeavor of Jesus Mamisao* and comparison of the time ratios produced by the Pi terms provided some justification for assuming the predominance of the gravity term.

Finally, a length scale ratio of 1:175 was selected; and, under the hypothesis just discussed, 1:13.25 was used for the time ratio. With these scale ratios and the other conditions discussed, the two major components (topographic model and rainstorm simulator) of the hydrologic model were designed and constructed.

Model construction

Topographic Model

For the study, a 97.2-acre semiarid Agricultural Research Service experimental watershed (Montaño No. 1), located approximately 20 miles northwest of Albuquerque, New Mexico, was selected as the prototype watershed. What little soil has developed on this watershed is badly eroded, and the land has been described as rough, broken badland, 77 percent of which is barren. For the most part, the watershed has a well-developed channel system with miniature canyons cutting through sandstone in the central part of the basin.

The needs for the topographic model required that it be fabricated from a material that could be easily manipulated and that would permit easy future alteration and instrumentation. A preliminary investigation indicated that a hand lay-up fiberglass shell would fulfill the needs and that the entire model could be made in one piece.

Slides of a 5-foot contour map were projected on sheets of plywood which had been sanded to the proper thickness (0.343 inch) to represent a 5-foot

* Mamisao, Jesus, P. Development of an Agricultural Watershed by similitude. M.S. Thesis, Iowa State College, Ames, Iowa, 1952.

contour interval in the model. Each contour was traced onto separate sheets of plywood, and then the wood sheets were cut along the traced lines and positioned in a box encompassing the boundaries of the model watershed. The plywood sheets representing each contour were stacked in reverse order, the lowest point in the mold representing the highest point of the prototype watershed. The steps between the contours were smoothed by filling the indentations with a prepared plaster mix.

The plaster surface of the mold was made smooth and hard. Over the mold, fiberglas mat was laid and saturated with resin. When the resin had completely cured, the model was broken from the form, lifted up, turned over, and set on a supporting frame.

Rainstorm simulator

An analysis of seventeen selected storm events which occurred on the prototype watershed and the type of rainstorm typical to the location, indicated that the rainstorm simulator should simulate intensities from 0 to 10 inches per hour in increments of 0.01 inch per hour. Also there should be provision for doubling this range for future studies. After counting the changes of intensities during each storm event, provision for forty changes was considered adequate to accommodate even an unusual event. Thus, a device capable of simulating storm events ranging from low intensity rains to short-duration, intense thunderstorms, had to have good control over the application rate of the input liquid and variable areal coverage of the model.

Control over the application rate (simulated rainfall intensity) was provided by small positive-displacement gear pumps which supplied the input liquid at a rate proportional to the speed at which they were driven. The pumps were driven by variable-speed electric motors which were automatically controlled by commercial speed-controller units in conjunction with a specially designed switching circuitry.

Control over the areal distribution of the input was achieved by modular construction of the rainstorm simulator. Eleven modules, similar, but operating entirely independently, supplied input to only the fraction of the model watershed area covered by the particular module. Thus, by operating the group of modules independently but relative to one another, it was possible to simulate storm movement over the model watershed with varying precipitation intensities.

Ten of the modules were placed along the long axis of the watershed and one covered a small projecting arm of the watershed, as is illustrated in Fig. 1. Each module covers approximately 18 square feet which is an area equivalent to 12.6 acres in the prototype. Compared with the areal extent of convective thunderstorms, such articulation should be sufficient to represent

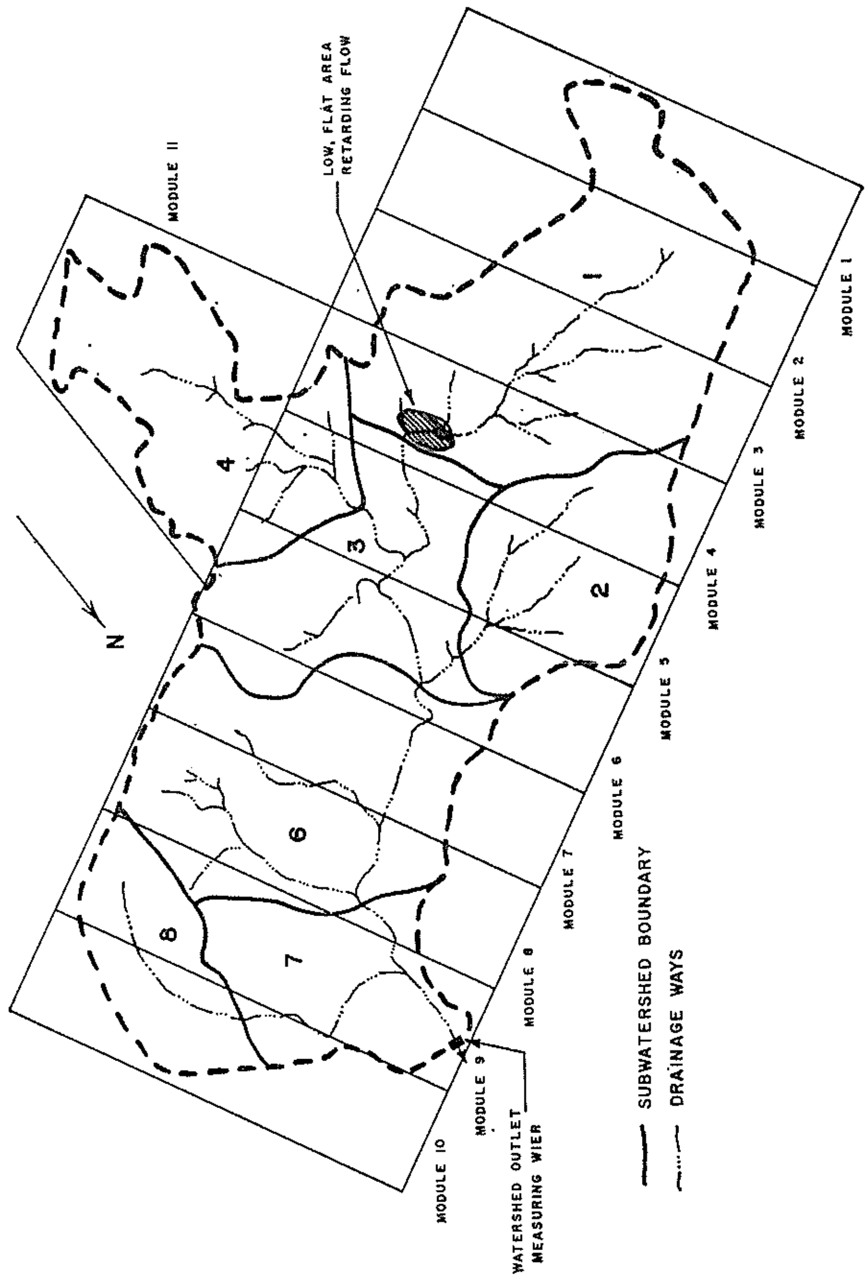

Fig. 1. Map of Montaño W-1 watershed with significant subwatersheds outlined and pattern of the simulator modules superimposed.

the intensity distributions and movement of these storms reasonably well.

Uniform liquid application within each module was attained by using 676, 2-foot-long capillary tubes (0.011 inch I.D.) to convey the liquid from a central source and distribute it evenly over the area covered by the module. The discharging ends of the tubes were positioned every 2 inches in the grid hanging over the topographical model.

A schematic drawing (Fig. 2) best illustrates how the various components were arranged into a complete simulator system. The characteristic and function of each component are given in the following explanation:

1. *Drum.* The drum is a 12-inch-diameter plastic cylinder drilled with holes in which pegs are inserted to control the on-off and running time of the pump motors in each module. With the initial assumption on the time relation between the model and prototype, the drum was designed to rotate at speeds which would represent:

(a) $\frac{1}{2}$-minute intensity changes for a total duration of 3 hours,

(b) 1-minute intensity changes for a total duration of 6 hours,

(c) or 2-minute intensity changes for a total duration of 12 hours.

The range in the time programming also provides latitude for the investigation and use of different time ratios if the need arises.

2. *Tripping switches.* As the drum rotates, the pegs trip these switches which activate the stepping switches.

3. *Stepping switches.* These switch, in sequence, a series of potentiometer settings into the motor speed controller circuits.

4. *Potentiometers.* The settings of the potentiometers control the motor speeds and consequently the input rates. A sequence of forty potentiometers allows for forty changes of input rate in each module for each operation of the simulator.

5. *Speed controller.* A commercial speed-controller unit, in connection with the potentiometers, operates to control the speeds of the pump motors.

6. *Motors.* Variable-speed DC motors turn the pumps.

7. *Gears.* In accordance with the rated pump displacement and speed capabilities of the motors, a gear reduction of 2:1 gave the desired input range.

8. *Pump.* A gear pump with a displacement of 0.836 cc per revolution delivers the input liquid to each module.

9. and 10. *Hose and Junction Manifolds.* The supply system.

11. *Distribution Heads.* Brass nipples are used as the junction point for 169 capillary tubes. Four such distribution heads are used in each module.

12. *Tubing.* The capillary polyethylene tubing (0.011 inch I.D.) is used to distribute the input liquid uniformly over the area of each module.

Outflow from the model was measured by funneling it into a cup located on the end of a pivoted arm. The arm was supported by a tension spring

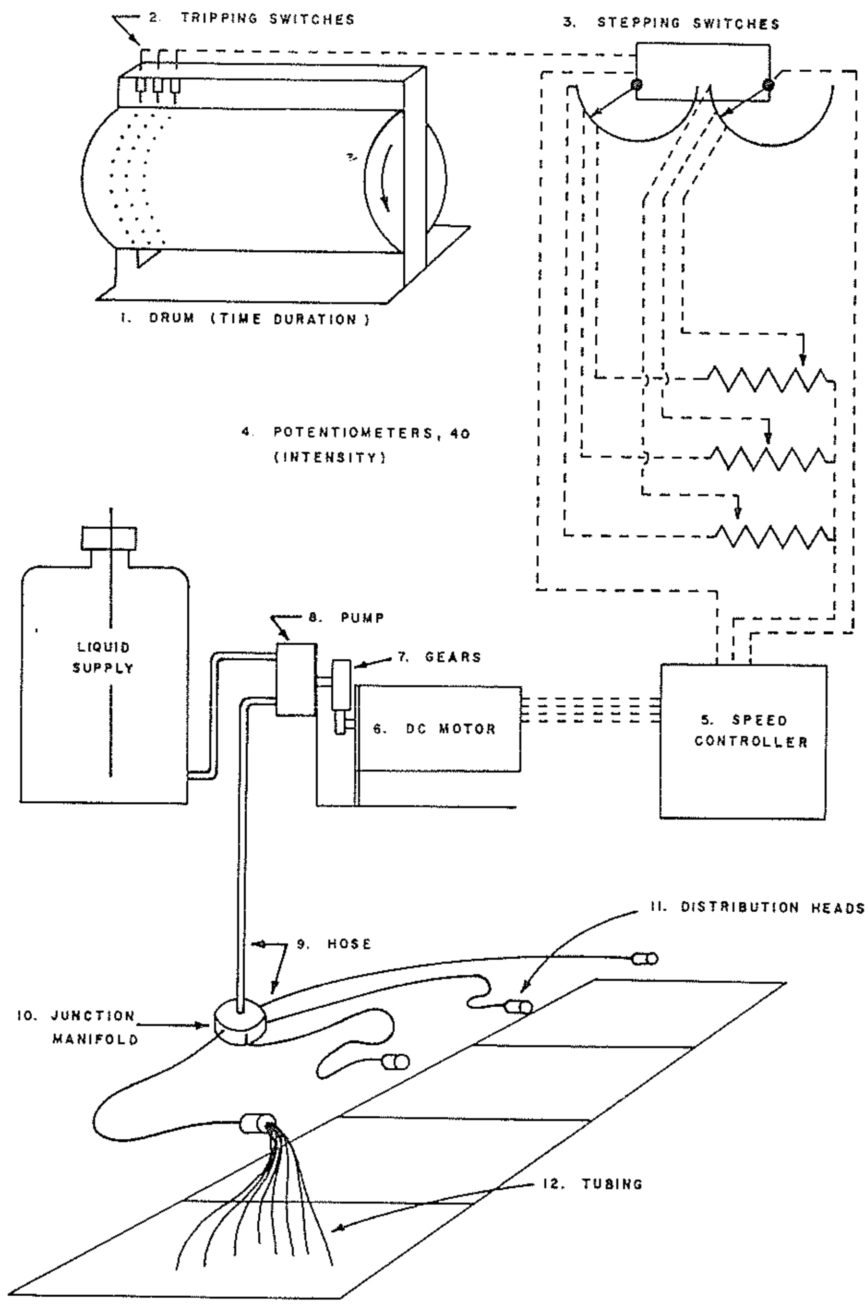

Fig. 2. Schematic drawing of the rainstorm simulator, illustrated for one of the eleven modules.

which stretched and allowed the arm to rotate about the privot as the liquid flowed into the cup. The rotation of the arm actuated a linear-motion potentiometer which fed a signal to a strip chart recorder. A curve of accumulated runoff versus time was recorded. With this system the recorder had the capacity to record 100 g of liquid. By changing cups, the range of the recording could be extended to any amount. This system was improved slightly during the course of preliminary model testing, but in general proved less than satisfactory, because the interruptions in the recorded record caused by the changing of the cups produced an interrupted record which was difficult to analyze, and the chart speeds of the recorder were too slow to give good resolution of the mass record into a flow rate record. Nevertheless, some interesting data were gathered which gave an indication of what might be expected from such a model.

Discussion of preliminary tests

Some preliminary experimental tests with the model gave an indication of its performance. One group of tests was the initial effort to program the rainstorm simulator with a scaled prototype rainstorm and to compare the outflow with the prototype hydrograph. A second group of tests was made with an idealized input.

A prototype rainfall-runoff event which occurred October 4, 1946 was selected for the preliminary tests. This particular event was chosen because of its simple rainfall intensity pattern and runoff hydrograph. The event consisted of two essentially uniform-intensity rain periods or pulses; the first of 1.20 inches per hour for 4 min, and the second of 4.35 inches per hour for 4 min. The smaller pulse occurred first, and the larger followed about 45 min later. The records also indicate that the storm moved from the west to the east end of the watershed.

As has been described, the model has an impervious surface, but such a surface does not result in 100 percent runoff. Experience indicated that no outflow would occur if the scaled storm was applied to the dry surface using distilled water as the model liquid. To assure an input excess and outflow from the model, two test variations were made that would compensate for the initial storage. In one variation, the surface storage was satisfied, and then the scaled input applied. In the second variation the input rates were magnified. The tests conducted in this series are summarized in Fig. 3. No outflow results when the scaled input is applied to a dry model surface, as is indicated by the results of "F" series tests. Information from all the tests indicated that at least 2250 cc of distilled water could be held on the surface of the model by the forces which developed between the water and the

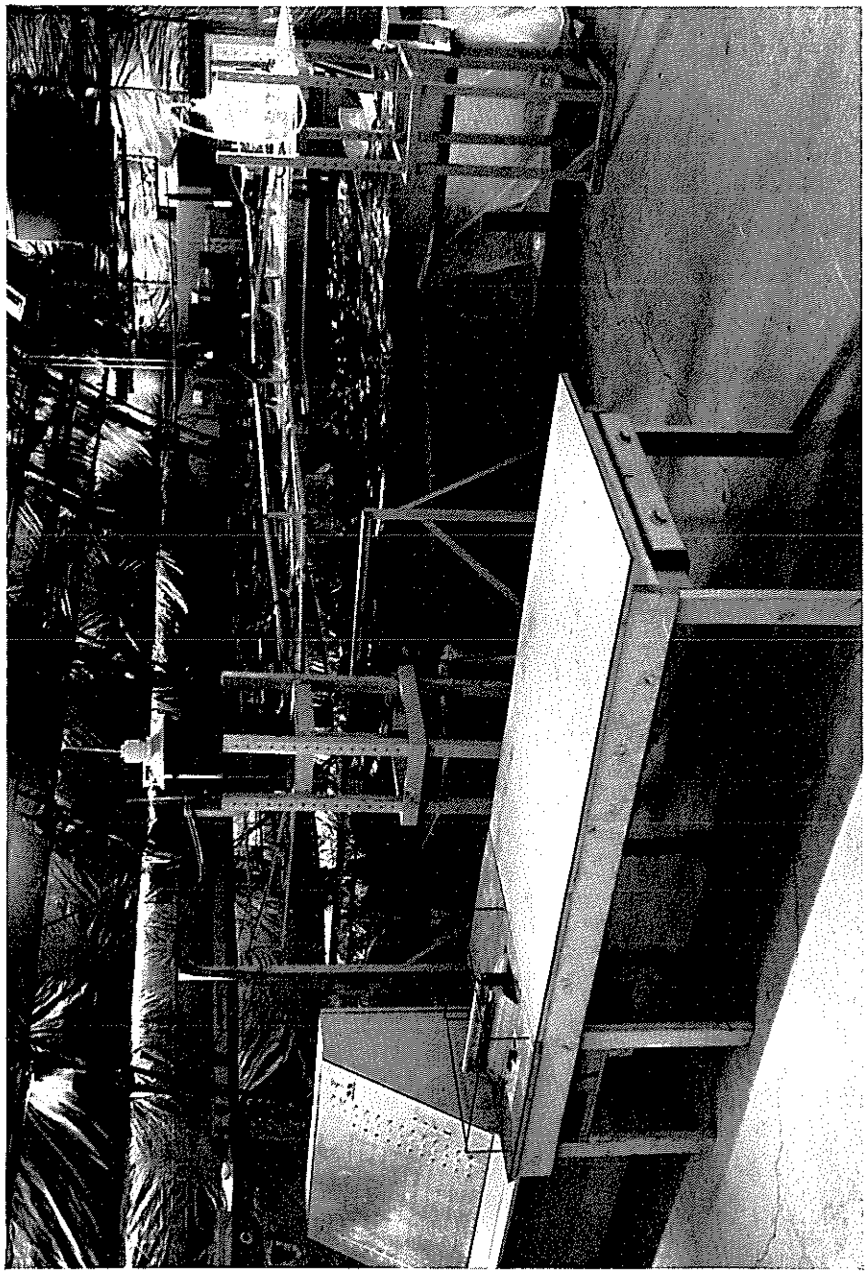

Fig. 4. Overall view of topographic model, rainfall simulator, and control console.

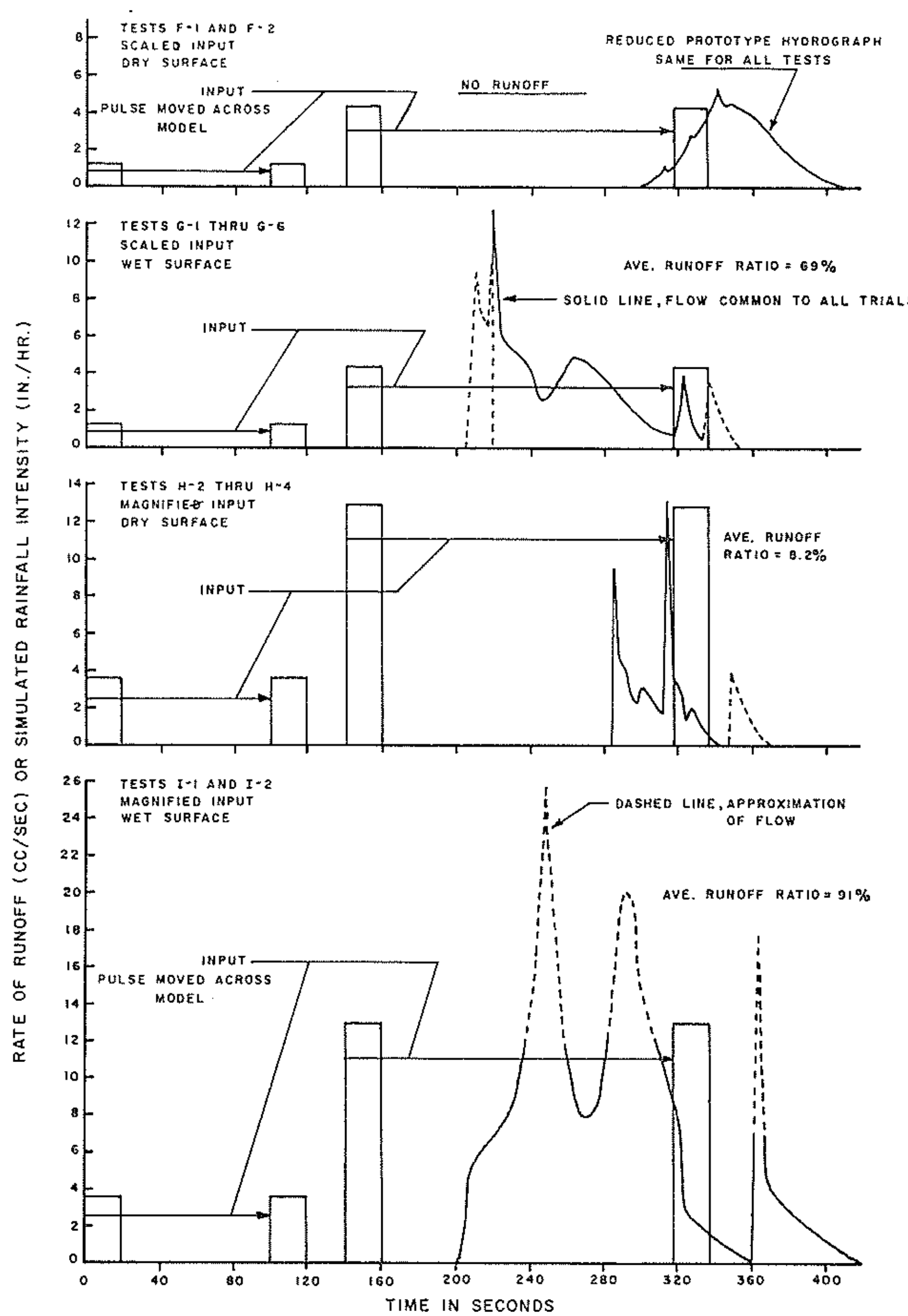

Fig. 3. Summary of test results from the simulation of the October 4, 1946 prototype storm event.

fiberglas surface. A description of the water flow on the model surface may give an appreciation for the considerable amount of surface storage. The water dropped from the rainstorm simulator and formed small globules on the polished surface in the same way raindrops bead on the waxed surface of an automobile. The globules grew, and when they became of sufficient size (about 2.5 cm in diameter), they would suddenly leave their place and flow over the surface as a small slug of water. The storage was contained in all the small globules scattered all over the surface of the model.

The outflow of the "H" series tests began within 15 sec of the 300-sec beginning times of the prototype hydrograph scaled by the time relation derived from the gravity criterion. These preliminary results in no way assure the gravity time relation as the proper time relation. The time relationship must be investigated further.

The outflow to input ratio of the "H" series tests was about 0.08. The same ratio for the prototype was 0.38, which indicated that almost five times more input appeared as outflow in the prototype than in the model. As a consequence, comparison between the model and prototype outflows was difficult. The thin, compressed, double-peaked model hydrograph is quite unlike the reduced prototype hydrograph. The threefold magnification of the input rates was barely sufficient to cause outflow from the dry model. Further, the model outflow which did occur came from the number two area (Fig. 1) and areas adjacent to the main channels. It was concluded, therefore, that if the model surface was initially dry, either greater magnification of the input rates or alteration of the fluid-surface interaction would be needed to overcome the large initial surface storage.

The preliminary tests revealed the need for improved measurement of the outflow and more consistent mechanical performance. The causes for inconsistent performance could be traced more easily by using an idealized situation. Also, further information about the nature of the flow from the model could be obtained. In the course of conducting these tests, numerous mechanical improvements became apparent, and the information from the tests indicated that the problem of consistent performance was largely physical and could be rectified by the proper modification and sophistication of the equipment.

Summary and Conclusions

The development of the design for a physical hydrologic model has been reviewed and the salient points of the model construction described.

Model performance during a series of preliminary tests was discussed. Information from these tests and the experience with the model encourage the continued development of such models, but they also reveal that many questions must be studied and answered before satisfactory modeling relations are developed. Information from the tests indicated that the assumption of the gravity ratio as the determinant of the time relation only came close to giving the proper time relation in the one case of magnified input on a dry model surface. The determination of the proper time relation then becomes one of the most important undertakings. Not only must the proper time relation be developed, but also the throughflow abstractions or input excess must be regulated so that the outflow-to-input ratio in the model is on the same order of magnitude as the prototype runoff ratio. Both of these investigations will entail a comprehensive study of the liquid-surface interaction (which will be studies with liquids of different physical properties and various surfaces), distorted inputs both in the length and time scales, and vertical scale distortion of the topographic model.

Investigations also need to be made of the permissible length scale ratios which may be used in the topographic model in relation to the scales used in the rainstorm simulator.