Surface Water Hydrology, 1

Frederick Room **08h 30m, April 10**

(H23) • WALTER T. SITTNER, • CHARLES E. SCHAUSS, • JOHN C. MONRO (ESSA, Weather Bureau, Silver Spring, Md.), *Continuous Hydrograph Synthesis with an API Type Hydrologic Model.* The U. S. Weather Bureau Hydrologic Research and Development Laboratory has developed a complete hydrologic model that utilizes an antecedent precipitation index (API) type rainfall-runoff relationship to compute surface runoff. With ever-increasing demand for continuous river forecasts as well as flood forecasts, it has become necessary to have a model that will predict all components of flow as functions of observable independent parameters and on a continuous basis. To formulate the complete model, existing and proved techniques were used where possible, and new techniques were developed as necessary. The model consists of four basic parts: a relationship for computing ground water recession, a method of computing the ground water flow hydrograph as a function of the surface runoff hydrograph, an API type rainfall-runoff relationship, and a unit hydrograph. The rainfall-runoff relationship is of the incremental type, providing a runoff computation for each 6-hour period rather than computing the total storm runoff as was done by previously used relationships. This has been accomplished through the inclusion of a new parameter, a 'Retention Index.' Two important features of the model are ease of adjusting parameters to observed flow and sequential development of the four basic parts with a minimum of interaction.

(H24) • C. A. ONSTAD, • D. L. BRAKENSIEK, (U. S. Agricultural Research Serv., Soil and Water Conservation Research Div., Beltsville, Md.), *Simulation of a Watershed Drainage System by Natural Stream Path Analogy.* The hydrograph predicted at the outlet of a watershed is very often the result of routing lumped inputs. In this study, an outflow hydrograph is synthesized by routing input distributions superimposed on a natural flow system. The natural flow system is developed from stream lines constructed on a contour map of the watershed. Overland flow is routed through these stream tubes to an intersection with an appropriate channel. Channel flood routing is then performed down to the outlet, with the calculated overland flow as input. Possible optimizations of the system parameters are studied.

(H25) • D. L. CHERY, JR., (U.S. Agricultural Research Serv., Southwest Watershed Res. Center, Tucson, Ariz.), *Output Response of a 'Scaled' Laboratory Watershed System Caused by Various Step Inputs.* A 'scaled' laboratory watershed model of a prototype semiarid, 97-acre watershed has been reported on. Step inputs, using distilled water and variations of four intensities and four durations, were applied to this laboratory watershed system and the output response recorded. Output responses were also recorded for step inputs using sodium sulfonate-water mixture and ethyl alcohol. The results of these tests indicate, to an extent, the influence on the output of input rate, input duration, and differences in system storage. These results are analyzed, and the model outputs are compared with selected prototype outputs. In general, the results indicate that inputs to the model must have rates on the order of or greater than the highest test rates and durations on the order of the shortest test durations, and that the model storage must be increased to have the model system perform similarly to the prototype system.

(H26) • DONALD L. BENDER (Civil Engineering Dept., Washington State Univ., Pullman), • ALAN E. HASTINGS (U. S. Corps of Engineers, Portland, Ore.), *Unit Hydrograph Variation with Time of Occurrence.* An 8-foot by 16-foot laboratory catchment was used as a hydrologic system to test certain relationships between rainfall and runoff. Unit hydrographs were obtained for a variety of catchment conditions and rainfall intensities and durations. A technique of isolating 1-minute duration rainfalls within the total rainfall duration allowed 1-minute unit hydrographs to be obtained for different times of occurrence. A series of curves for each separate set of rainfall and catchment conditions for these 1-minute unit hydrographs illustrates that the peak of these 1-minute unit hydrographs increases until the time of equilibrium is reached. After reaching the time to equilibrium the peaks remain constant, and for any given catchment condition the maximum peak discharges of the 1-minute unit hydrographs are the same regardless of intensity. Also for a given catchment condition with the duration of rainfall greater than the time to equilibrium, the peak discharges of the total time duration unit hydrographs are the same regardless of intensity. Time to peak on the catchment is related linearly to the time to equilibrium. Correlations between observed relationships on the catchment and on natural streams indicate that the laboratory system responds to rainfall in a manner similar to that of natural basins.

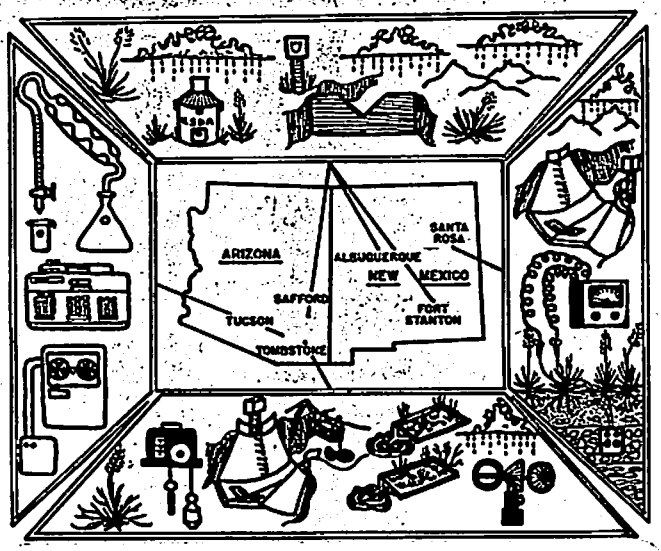
(H27) • VEN TE CHOW, • BEN CHI YEN (Univ. of Illinois, Urbana), *A Laboratory Study on the Effect of Moving Rainstorms on Surface Runoff.* Through the use of the Watershed Experimentation System, a laboratory apparatus capable of producing rainfall of variable space and time distributions, the time distribution of runoff from square and triangular impervious surfaces of uniform overland and channel slopes is investigated. The rainstorms under consideration have uniform

CHERY

Output Responses to Pulse Inputs of a Scaled Laboratory Watershed System.

56

UNITED STATES DEPARTMENT OF AGRICULTURE
AGRICULTURAL RESEARCH SERVICE
SOIL AND WATER CONSERVATION RESEARCH DIVISION



PRELIMINARY DRAFT - NOT FOR PUBLICATION

PUBLICATION OF
SOUTHWEST WATERSHED RESEARCH CENTER
TUCSON, ARIZONA

IN COOPERATION WITH
U.S. SOIL CONSERVATION SERVICE,
UNIVERSITY OF ARIZONA,
NEW MEXICO STATE UNIVERSITY
AND UTAH STATE UNIVERSITY

AUG 21 1968

OUTPUT RESPONSES TO PULSE INPUTS OF A "SCALED" LABORATORY WATERSHED SYSTEM [1/]

D. L. Chery, Jr. [2/]

INTRODUCTION

The development of scaled models of the hydrologic system and laboratory catchments has been discussed during the past five years. With respect to this interest in laboratory catchments, and with the sponsorship of the Agricultural Research Service, I attempted to build a physical model (scaled) watershed system. This ambitious objective was eventually discouraged by the complexities of the physical system and the inadequacies of scaling theories and technology. Nevertheless, a laboratory apparatus was built and some tests conducted on it which were reported as "preliminary verification of a physical hydrologic model," (Chery, 1965). A set of exploratory tests was made in the summer of 1965, making use of the physical model as a small laboratory catchment system. The results of these tests are reported here for what they may contribute in the development of laboratory catchment systems.

[1/] Contribution of the Southwest Watershed Research Center, Soil and Water Conservation Research Division, Agricultural Research Service, USDA, in cooperation with the Utah Water Research Laboratory, Utah State University, Logan, Utah and the Arizona Agricultural Experiment Station, Tucson, Arizona.

[2/] Research Hydraulic Engineer, Southwest Watershed Research Center, USDA, Agricultural Research Service, Soil and Water Conservation Research Division, 442 East 7th Street, Tucson, Arizona.

EXPERIMENTAL DESIGN

Objectives: The experiment was designed to be exploratory. The specific questions to be explored were:

1. What was the laboratory model watershed response to a set of discrete pulse inputs? A pulse is the application of the input of a constant rate for a definite duration of time. The input set was to span a range of application rates and durations.
2. What were the responses to continuous inputs of various application rates?
3. What were the responses when liquids other than distilled water were used?
4. What were the surface storages in the model system?

Design of the Tests: The set of tests conducted is listed in Table 1. All tests with distilled water had two or more repetitions. When the tests with the sodium sulfonate-water mixture were made, the outputs were so similar that only one repetition was made. When the alcohol tests were made, we were fortunate to get just the three tests, because the alcohol fumes became overwhelming and some parts of the apparatus began to disintegrate.

The durations of the pulse inputs were determined after the test in which input was applied continuously until the outflow reached equilibrium. Three ending times for the duration of input pulses were selected from the times between the beginning of outflow and equilibrium outflow. A common input duration of 100 seconds was

Table 1. Set of tests conducted on laboratory watershed model, July 1965

Type of test	Designed input rate	Duration	Number of trials	Average measured input rate
	(cm/sec) x 10^{-4}	(seconds)		(cm/sec) x 10^{-4}
A. With distilled water as input liquid on surface of polished plastic	6.880	to equilibrium	5	6.506
	6.880	100	3	6.500
	6.880	70	3	6.604
	6.880	40	3	6.495
				6.523 (all tests)
	5.159	to equilibrium	3	4.637
	5.159	130	3	4.907
	5.159	100	3	5.004
	5.159	70	3	4.420
				4.781 (all tests)
	3.439	to equilibrium	3	2.941
	3.439	160	3	2.952
	3.439	130	3	3.055
	3.439	100	4	2.935
				2.964 (all tests)
	1.720	to equilibrium (no pulse tests)	3	1.548
B. With distilled water as input liquid on surface covered w/paper toweling.				
(dry towel)	5.159	to equilibrium	1	4.655
(wet towel	5.159	100	1	4.700
C. With a 0.1% mixture of sodium alkyl aryl sulfonate and distilled water as input liquid.	5.159	to equilibrium	2	4.700
	5.159	100	2	4.901
	5.159	70	2	4.987
				4.792 (all tests)
D. With 100% ethyl alcohol as input liquid.	5.159	to equilibrium	1	4.351
	5.159	100	1	4.242
	5.159	70	1	4.506
				4.368 (all tests)

selected for tests with each different input rate and liquid. When the 1.720×10^{-4}-cm/sec input tests were begun, it was realized that the application rate was too low to cause useful output responses to pulse inputs; so only the equilibrium outflow tests were made.

As an afterthought, two tests were made with the surface of the model covered with paper toweling to observe the effect of a change in the model surface on the output.

Apparatus and Instrumentation: The laboratory watershed model used for these tests had two main components -- a scaled topographic model of a 97-acre semiarid watershed and a rainstorm simulator. (See Figure 1 for a photograph of the apparatus.) The surface of the topographic model was polished plastic. A topographic map (Fig. 2) of the watershed modeled illustrates the surface configuration of the model. The model has been described in detail in previous reports (Chery, 1965 and 1966). For the tests being reported, better instrumentation was used to measure the outflow rate than was used in the preliminary verification tests (Chery, 1965 and 1966). The measuring device was a 1-inch-wide plastic channel with vertical sides and a very slight V-notch the entire length of the bottom. Outflow from the model flowed through this channel and fell freely into a container. The depth of liquid in the channel was measured by a sensitive capacitance gage. Prior to each day of testing, the measuring channel was rated by volumetrically measuring flow rate versus the measured depth. The depth signal was recorded against time on an oscillograph.

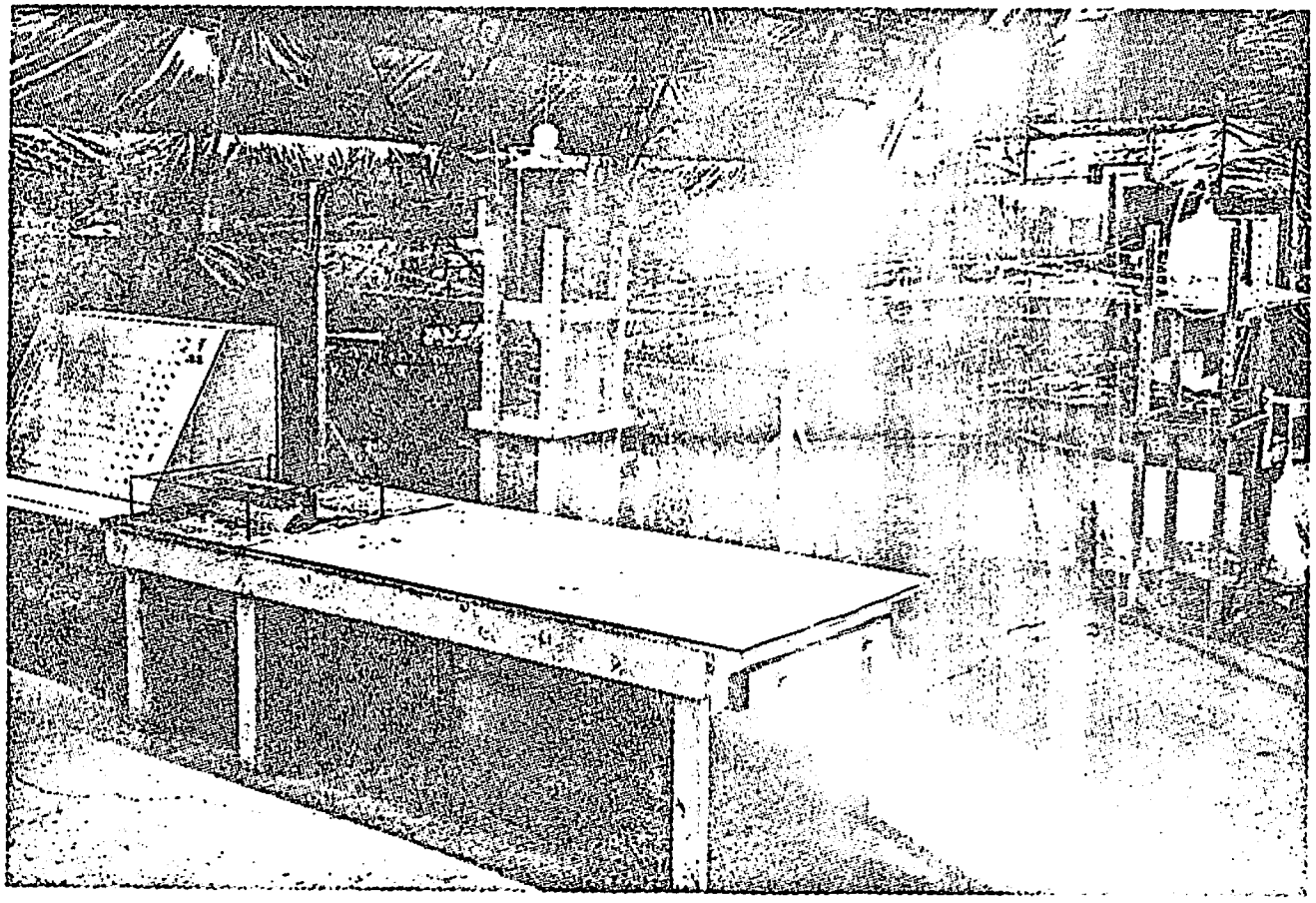


Figure 1. Overall view of the topographic model, rainfall simulator, and control console.

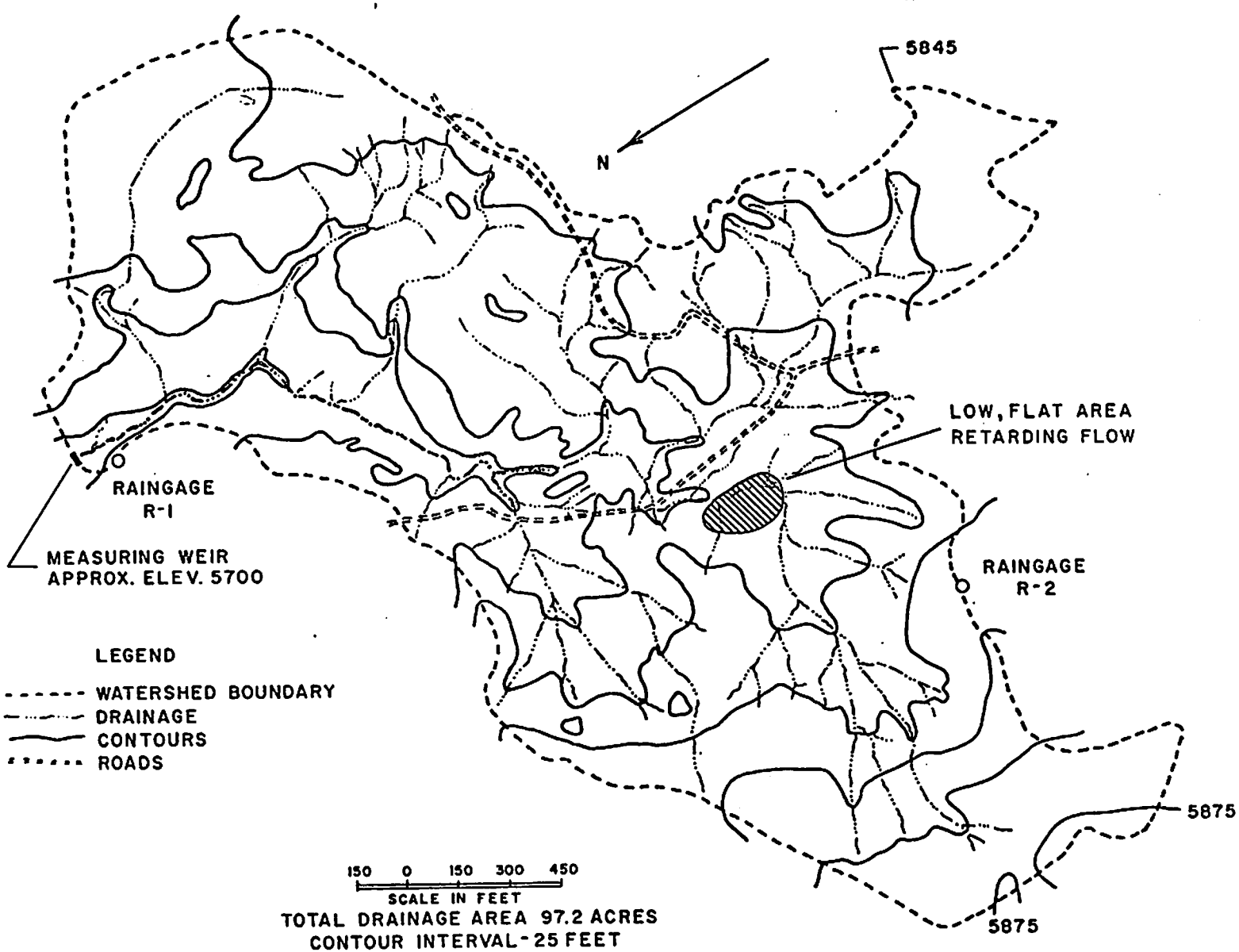


FIGURE 2. TOPOGRAPHIC MAP OF WATERSHED W-1, LOCATED ABOUT 19 MILES WEST OF ALBUQUERQUE, NEW MEXICO.

RESULTS OF TESTS

The results of the tests are the outflow records and measurements of storages in the model system. These outflow records are summarized in Figures 3, 4, and 5. The results of the storage measurements are summarized in Figures 6 through 10.

The summaries of the tests with water and sulfonate-water mixture were prepared by a visual averaging of the outflows for the tests and their repetitions. The results of a test and its repetitions appeared as those illustrated in Figure 3. Only a sample of the individual outflow responses caused by three different input rates for a 100-second duration is illustrated, but it shows, sufficiently, how the original data appeared when the repetitions were superimposed. From these superimposed plots, an average curve was drawn in by eye. This unobjective method was considered adequate for the repetition obtained and with respect to the exploratory nature of the experiment.

DISCUSSION

Output Response of the Laboratory System: In general, the response of the laboratory catchment system was consistent. The difference between a test and its repetitions as illustrated in Figure 3 and the differences between the beginning portions of the 3.44×10^{-4}-cm/sec and the 5.16×10^{-4}-cm/sec composite plots in Figure 4 reflect the influence of several effects. The outflow-measuring instrument was much more precise than the control over the input rate. As an example, the input rates for the 6.88×10^{-4}-cm/sec tests varied between 6.31 and 6.80×10^{-4}-cm/sec.

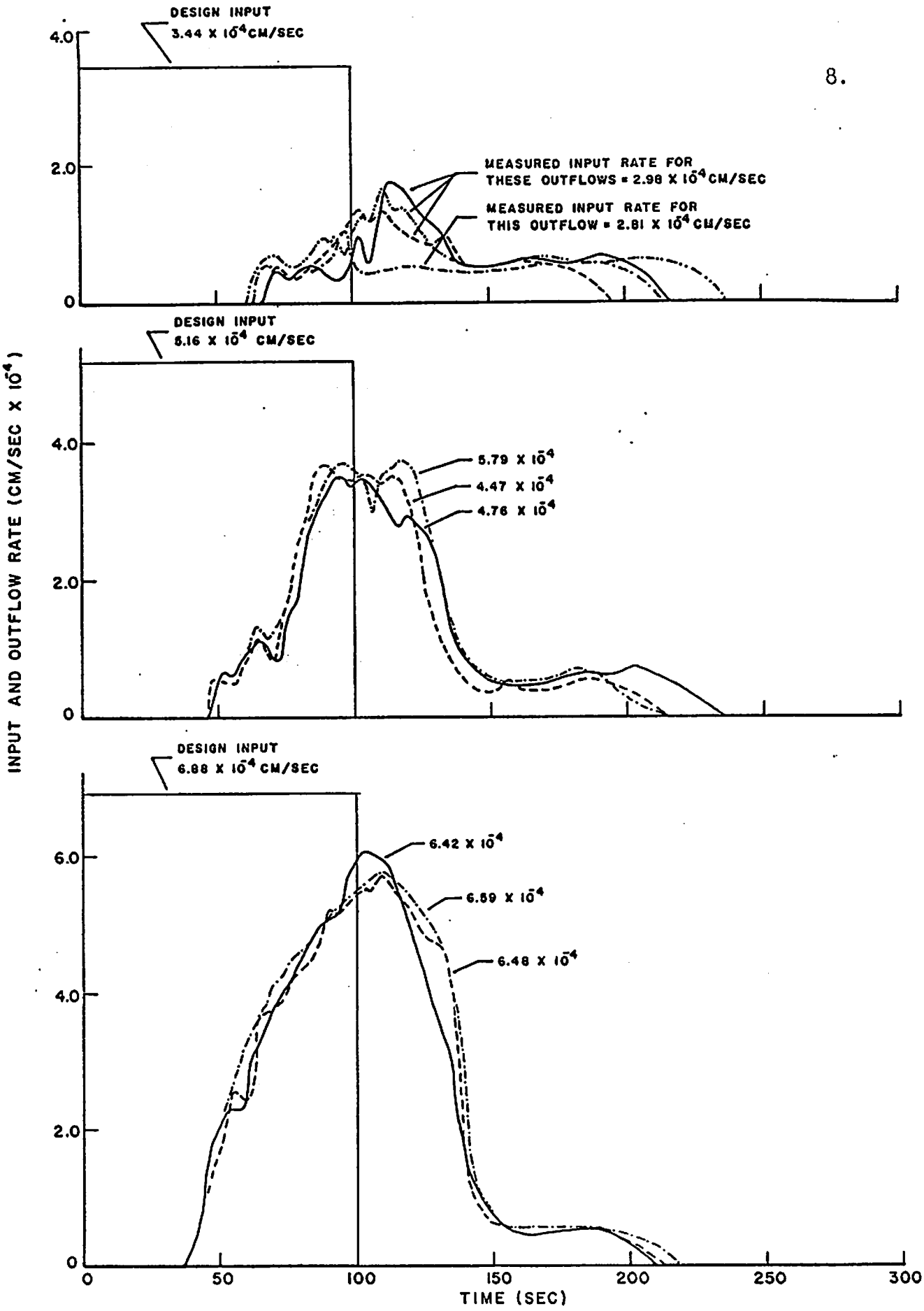


FIGURE 3. SUPERIMPOSED PLOTS OF OUTFLOW RESULTS FOR A TEST AND ITS REPETITIONS. INPUT LIQUID - DISTILLED WATER.

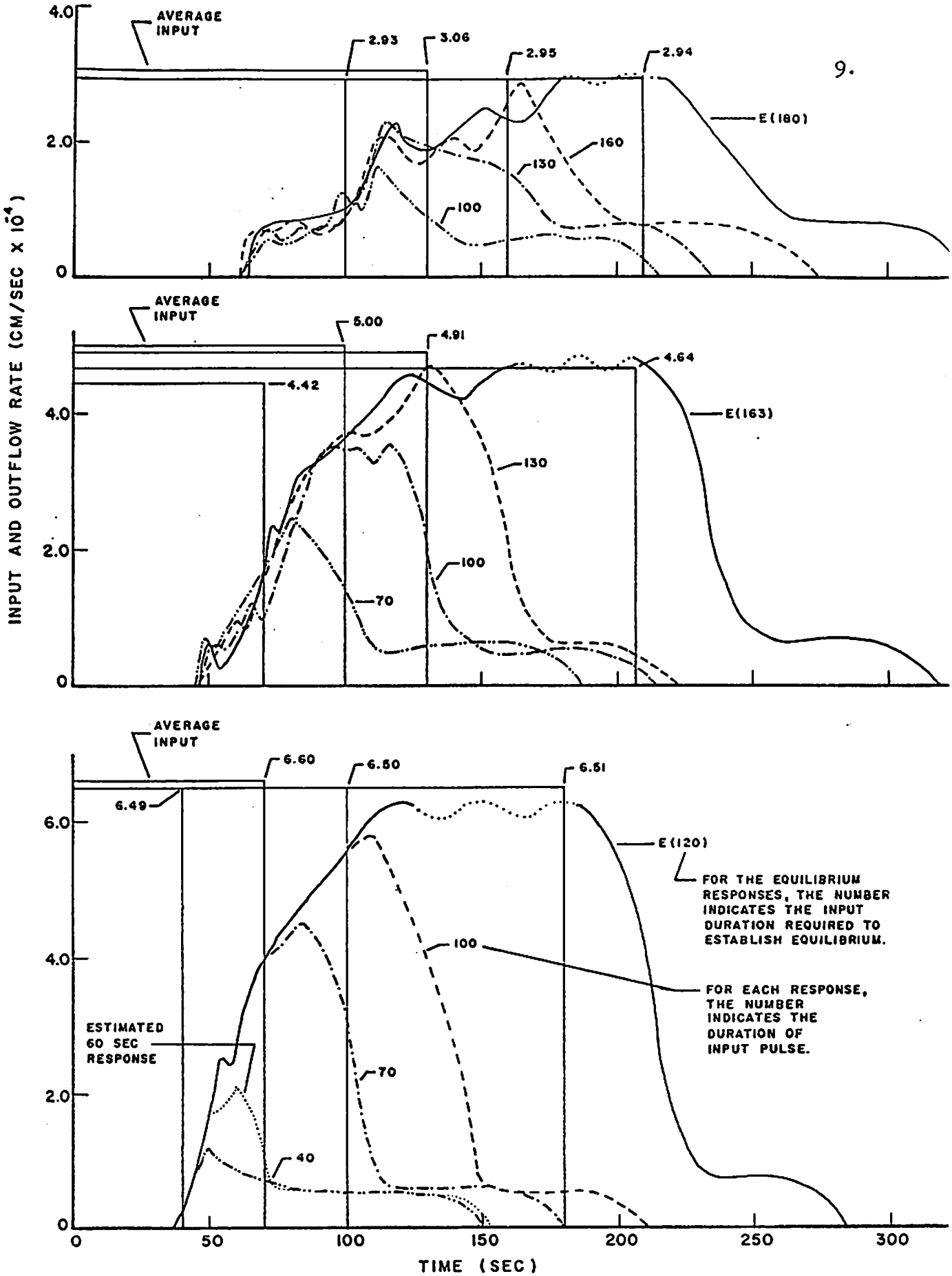


FIGURE 4. SUMMARY PLOTS OF LABORATORY CATCHMENT RESPONSES TO PULSE INPUTS OF DISTILLED WATER. EACH RESPONSE PLOT IS AN AVERAGE OF 3 OR MORE TRIALS.

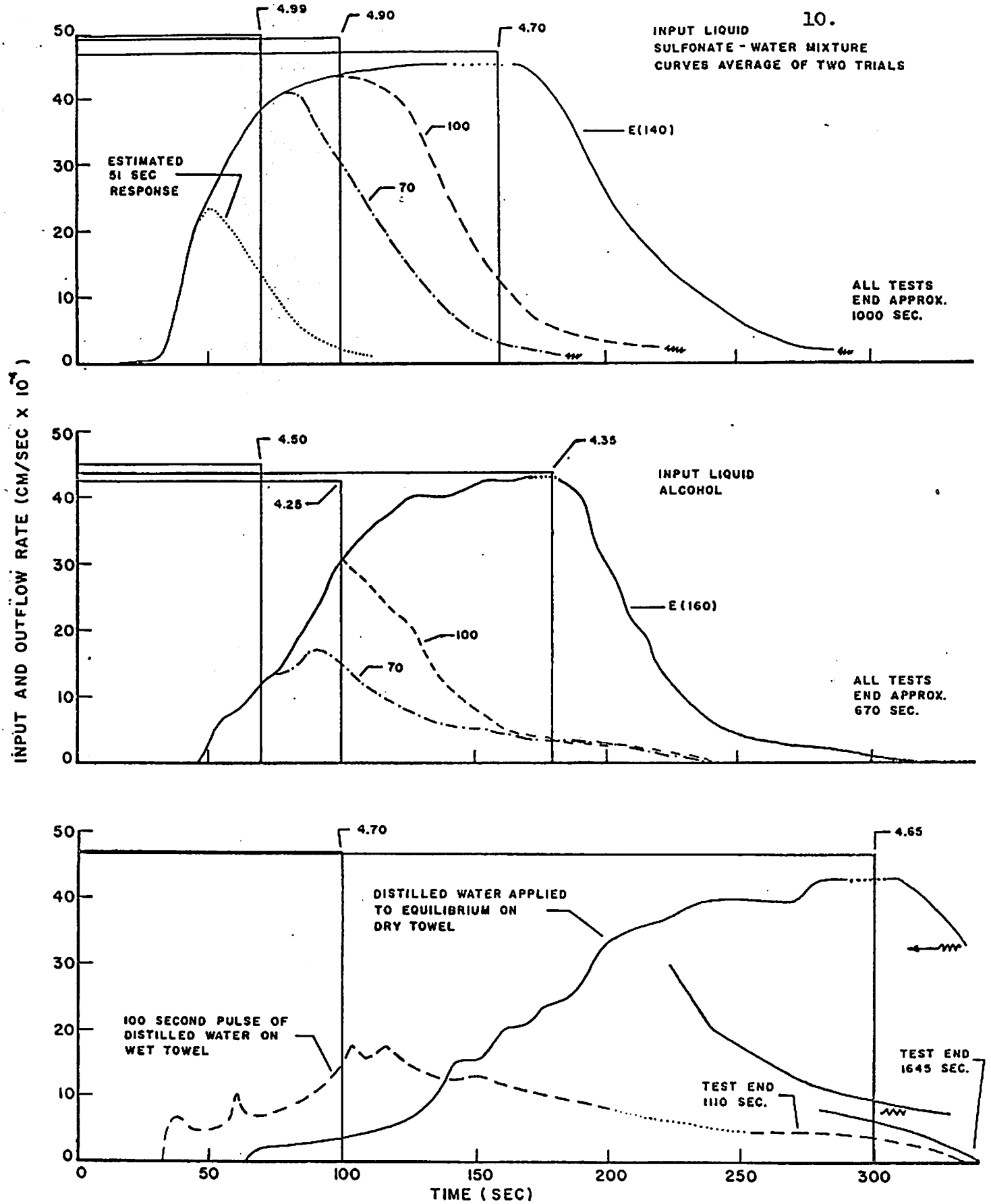


FIGURE 5. SUMMARY PLOTS OF LABORATORY CATCHMENT RESPONSES TO PULSE INPUTS AS INDICATED.

and those for the 3.44×10^{-4}-cm/sec tests varied between 2.52 and 3.28 $\times 10^{-4}$-cm/sec. The total volume of input liquid was determined by measuring the difference between before and after levels in the two large supply bottles. This measurement could be made to about $\pm$ 400 cc or about a 2% accuracy for the longest of the 6.88×10^{-4}-cm/sec tests and to about a 7% accuracy for the 3.44×10^{-4}-cm/sec tests. As these measurements and Figures 3 and 4 indicate, the lower the input rate, the greater the variation between tests. Such performance is to be expected from the rainstorm simulator, because the variable-speed motor-pump arrangement operates more uniformly at higher speeds and thus gives better control at higher input rates. In the tests using water, the outflow variation is also influenced by the particular water-surface interaction. The distilled water accumulated in large globules (up to 4 cm in diameter) on the plastic surface. These globules grew until they broke away and flowed over the model surface. At low input rates, this particular pulsating flow from the model surface contributed to the difference recorded between outflow of repeated trials. The influence of this water-surface interaction is reduced as the input rate is increased, and this is illustrated in Figure 4 by the several curves needed to represent the rising portion of outflow for the 3.44 and 5.16×10^{-4}-cm/sec input rates. But the rising portion of the outflows from 6.88×10^{-4}-cm/sec inputs could readily be represented by the single curve shown.

This observed relation between input rates and surface-liquid interaction suggests the use of higher input rates, which minimize the surface-liquid influence. Further, it is apparent that geometrically influenced output responses will be obtained with higher and higher input rates until the input submerges the control of the surface geometry. For this system, I do not know the input rate at which geometrical influence would disappear, but I can speculate that rates per unit area on the order of 1 cm/sec would fairly effectively flood the model. In comparison, the maximum input rate per unit area was about 0.00065 cm/sec. This comparison and the results obtained indicate that the rates used were near the lower limit of a useful range.

Another indication of the pulsating nature of the water flow through the model system is the undulation measured once "equilibrium" outflow was reached. This performance of water at equilibrium outflow is a contrast to that recorded when sulfonate-water and alcohol were used (Fig. 5).

From comparison of the system responses applying water at 5.16×10^{-4}-cm/sec (Fig. 4) and alcohol at the same rate (center plots of Figure 5), the rising portion of the alcohol response is similar to, but not as erratic as, the water response. The responses obtained when the sulfonate-water mixture was the input differ noticeably from those obtained with water and alcohol. The sulfonate-water response rose more rapidly toward equilibrium flow, and as a consequence, the responses

of both 70- and 100-second pulse inputs had nearly equal maximum outflow rates, which were near the equilibrium outflow rate. However, the alcohol response had a more persistent recession than the water response and, interestingly, shows a noticeable change in rate of recession with respect to input duration. The longer the duration of the input pulse, the more rapid the recession. But the responses to 5.16×10^{-4}-cm/sec inputs of water indicate that the recessions are similar once the input duration is greater than 70 seconds. The system responses to the 6.88×10^{-4}-cm/sec input rate of water also have similar recessions for the 70 and 100 second and equilibrium pulses. However, the recessions of responses to inputs of water appear to vary with respect to the input rate -- the greater the input rate, the steeper the recession (Fig. 4).

The causes for the distinctive hump at the end of the water response recessions are not known definitely, but I speculate that the flow from the surface of the model ended when the flow rate evened out at about 0.6×10^{-4}-cm/sec ($\simeq$ 7.5 cc/sec). Then the hump recorded drainage from the small distinct channel of the model. The portion of channel to which I refer is about 305 cm long and is indicated by the heavy drainage line in Figure 2. Roughly, the prism of water in this channel was 0.5 cm deep and 2 cm wide; thus, about 305 cc of water was stored in the channel. The hump on the discharge records measured about 7.5 cc/sec for about 50 sec to produce a volume of 375 cc.

Just what influence the geometrical configuration of the model surface (Fig. 2) had on the shape of the outflow response is speculation. The high part of the model (the area to the west of the north-south road, cutting the watershed in Figure 2) did drain rather efficiently to a low spot (indicated on the map). The water collected in this low spot for a period of time and then spilled into the channel to flow toward the outlet. This performance may be the cause of the jog in the rising portion of the outflow responses. The need to observe responses from inputs to subportions of the model or to use tracers to gain some information on the geometrical influence of this system becomes apparent.

No comparisons are made of the equilibrium response to the 5.16 x 10^{-4}-cm/sec input of water on the dry towel surface with the responses of other tests, but this one test may give an indication of the long, stair-stepped type of response (Fig. 5) that may result if porous material is used on the model surface. Once equilibrium outflow was established, it was very even -- having none of the undulations or pulsations of the water flowing from the plastic surface.

Storage relations of the laboratory system: Figures 6 through 10 summarize the relation of the storage in the laboratory catchment, with respect to time and the outflow. The curves in Figures 6, 7, and 8 are a visual average of three or more tests. The curves in Figure 9 are a visual average of two tests, and those in Figure 10 are the results of the single test made with alcohol.

The storage was a nonunique hysteresis type function for all tests (each liquid, input rate, and input duration). In all tests

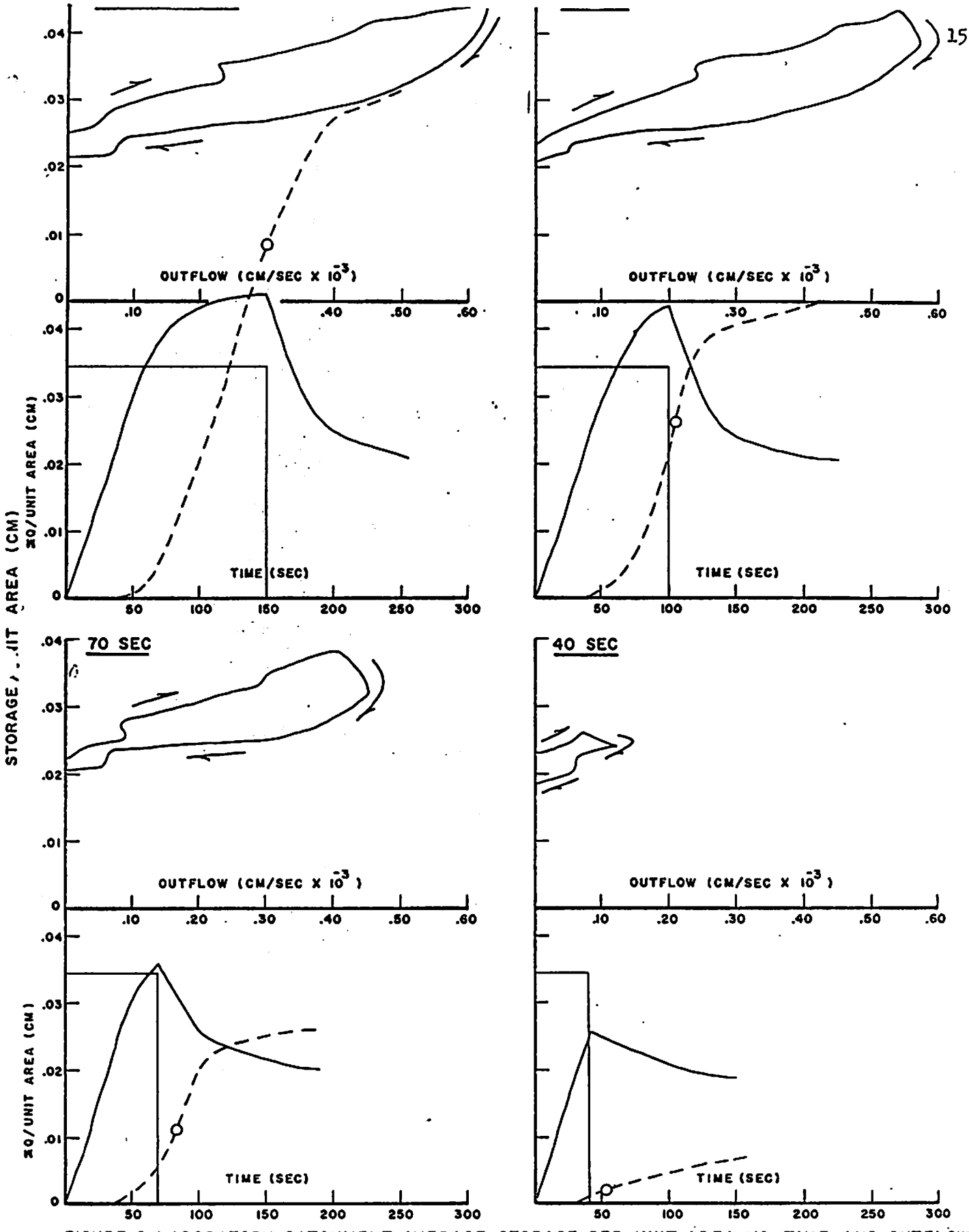


FIGURE 6. LABORATORY CATCHMENT AVERAGE STORAGE PER UNIT AREA VS. TIME AND OUTFLOW AVERAGE ACCUMULATED DISCHARGE PER UNIT AREA VS. TIME (DASHED LINE).
INPUT LIQUID - DISTILLED WATER
PULSE INPUT RATE/UNIT AREA 6.88 X 10^{-4} CM/SEC
PULSE DURATIONS - EQUILIBRIUM, 100, 70 AND 40 SECONDS

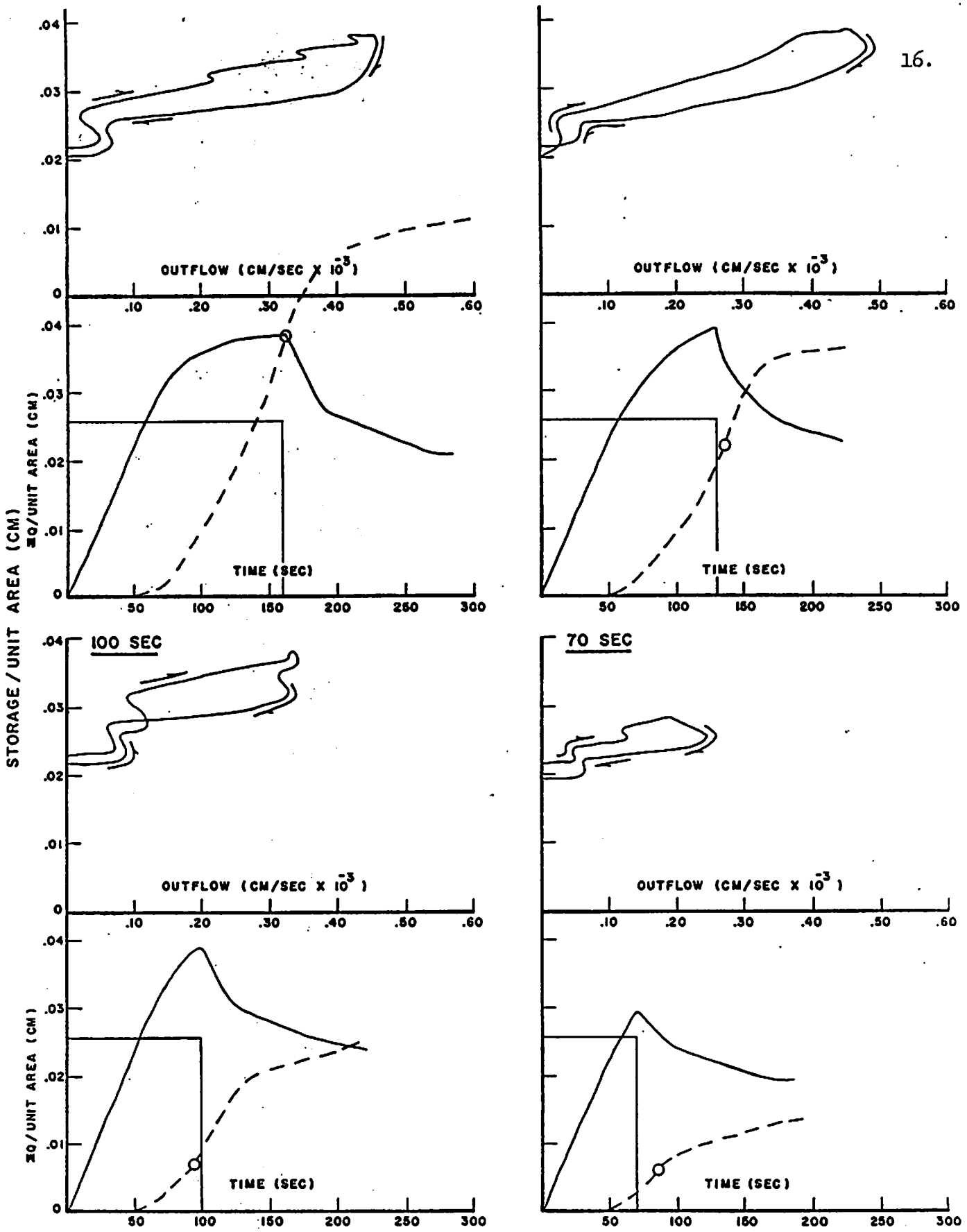


FIGURE 7. LABORATORY CATCHMENT AVERAGE STORAGE PER UNIT AREA VS. TIME AND OUTFLO
AVERAGE ACCUMULATED DISCHARGE PER UNIT AREA VS. TIME (DASHED LINE).
INPUT LIQUID - DISTILLED WATER
PULSE INPUT RATE/UNIT AREA 5.16 X 10^{-4} CM/SEC
PULSE DURATIONS - EQUILIBRIUM, 130, 100 AND 70 SECONDS

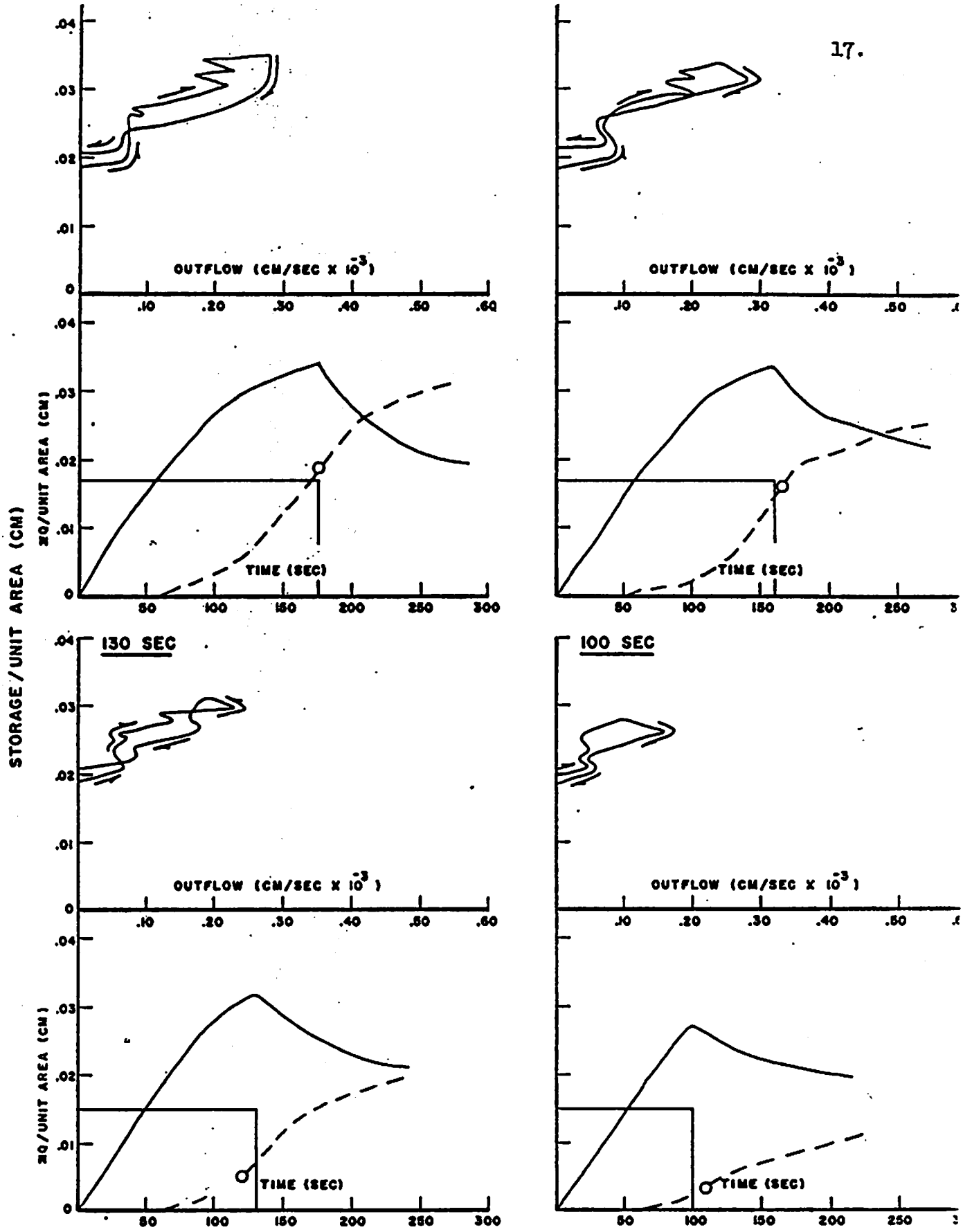


FIGURE 8. LABORATORY CATCHMENT AVERAGE STORAGE PER UNIT AREA VS. TIME AND OUTF
AVERAGE ACCUMULATED DISCHARGE PER UNIT AREA VS. TIME (DASHED LINE).
INPUT LIQUID - DISTILLED WATER
PULSE INPUT RATE/UNIT AREA 3.44 X 10^{-4} CM/SEC
PULSE DURATIONS - EQUILIBRIUM, 160, 130 AND 100 SECONDS

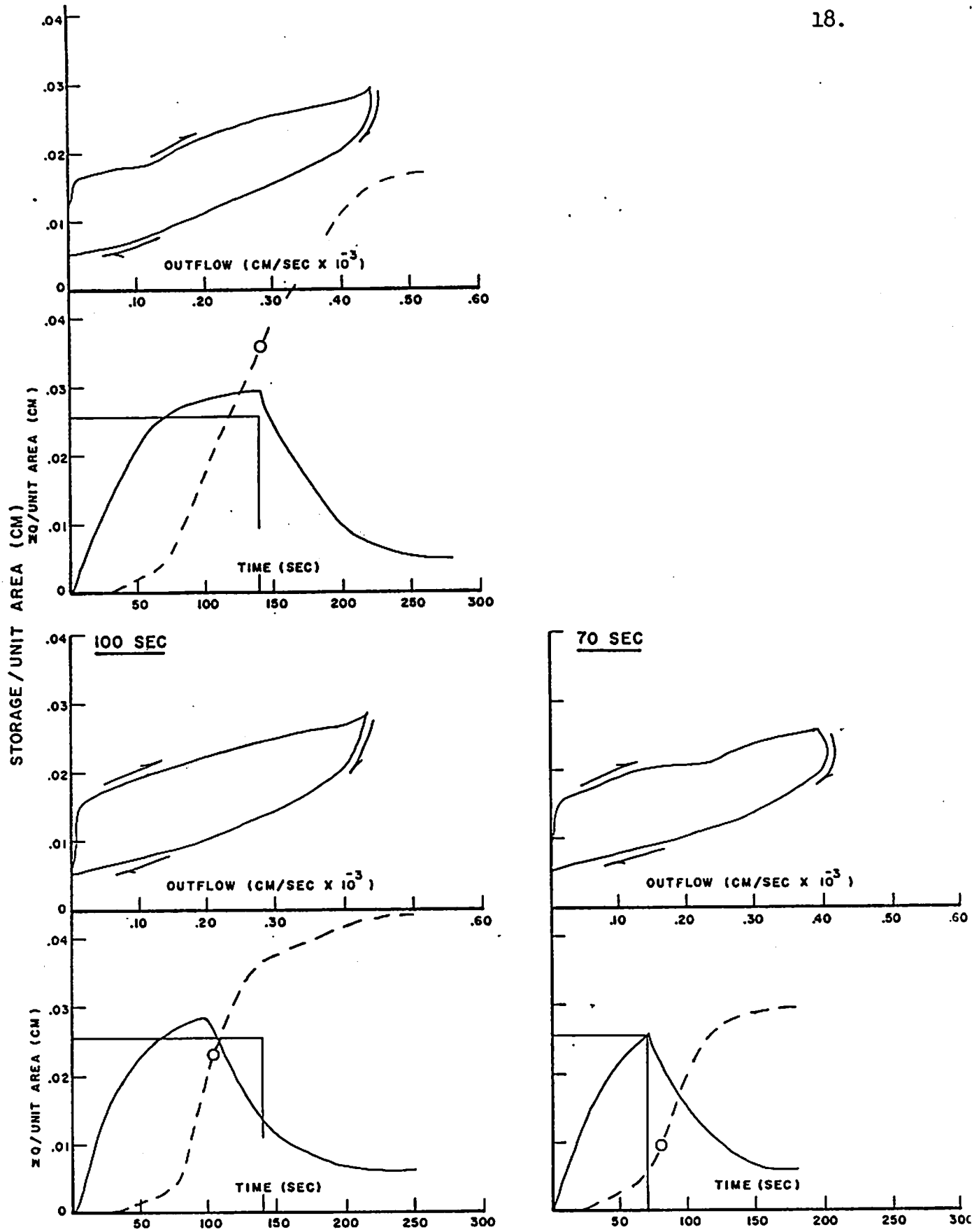


FIGURE 9. LABORATORY CATCHMENT AVERAGE STORAGE PER UNIT AREA VS. TIME AND OUTFLO
AVERAGE ACCUMULATED DISCHARGE PER UNIT AREA VS. TIME (DASHED LINE).
INPUT LIQUID - WATER - SODIUM SULFONATE MIXTURE
PULSE INPUT RATE/UNIT AREA 5.16 X 10^{-4} CM/SEC
PULSE DURATIONS - EQUILIBRIUM, 100 AND 70 SECONDS

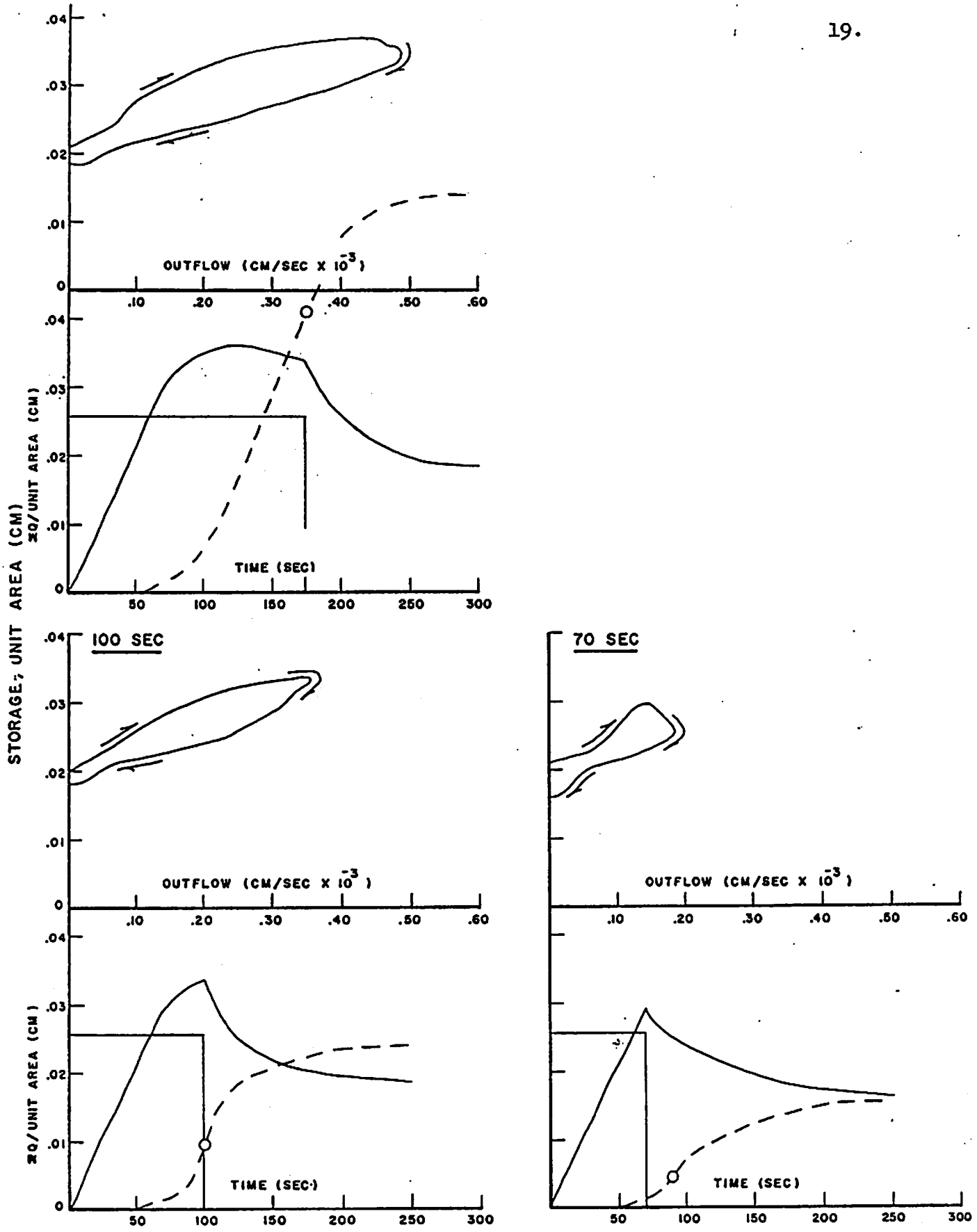


FIGURE 10. LABORATORY CATCHMENT AVERAGE STORAGE PER UNIT AREA VS. TIME AND OUTFLOW AVERAGE ACCUMULATED DISCHARGE PER UNIT AREA VS. TIME (DASHED LINE).
INPUT LIQUID - 100% ETHYL ALCOHOL
PULSE INPUT RATE/UNIT AREA 5.16 X 10^{-4} CM/SEC
PULSE DURATIONS - EQUILIBRIUM, 100 AND 70 SECONDS

(except the 130-second pulse of water at 3.44×10^{-4}-cm/sec test, Figure 8), the storage was greater while the outflow was approaching its peak rate than during the recession phase of the outflow. The results are nearly consistent in showing that the greatest storage occurred at the peak discharge for only the equilibrium tests. The exceptions were the 100-second pulse of water at 5.16×10^{-4}-cm/sec, 100-second pulse of water-sulfonate mixture, 100-second pulse of alcohol and equilibrium input of alcohol. The simultaneous peak storage and peak discharge for the 100-second pulse, water-sulfonate mixture test is understandable, because the response of 100-second pulse was nearly that of an equilibrium test (Fig. 5), but with the limited data it cannot be explained definitely. The reversal of storage-outflow relations in the alcohol tests is interesting, but again there are insufficient data for an explanation. With alcohol, the maximum storage occurred before peak outflow in the equilibrium test, and then in the 100-second pulse test the peak storage and outflow occurred simultaneously.

When water was used, an initial storage occurred before outflow began. This storage varied from .018 to .019 cm for an input rate of 3.44×10^{-4}-cm/sec to a storage of .022 to .025 for an input rate of 6.88×10^{-4}-cm/sec. The initial storage which occurred with the water-sulfonate mixture input was between .007 to .012 cm; less than that which occurred with water. The initial storage which occurred with alcohol was about .021 cm, which was about the same as that which occurred with input of water.

The sulfonate-water mixture began to "ooze" off the surface in about 11 seconds after the input began. Significant outflow began in

30 seconds, which was sooner than outflow began when either water or alcohol was used. Both the alcohol and sulfonate-water mixtures spread as an even-flowing film over the surface of the model.

The easy flow of alcohol and sulfonate-water over the model surface is further reflected in Figure 11, which shows 200-300 cc. of these two liquids remained on the surface after each test as contrasted to about 2,500 cc of water remaining at the end of a test. Each point in Figure 11 represents a measured residual storage at the end of a test. There is an indication of a slight increase in residual storage with increased input rate. The input rate, in itself, should not influence residual storage. What should possibly be inferred is that there was more complete distribution of water over the surface of the model at the higher rates that satisfied more of the maximum residual surface storage of this system. Still, there was considerable variation among the residual storages at the highest input rates. Explanations for this variation are among the factors of a rather crude measuring method, progressive wetting of the model surface with each test, instability of the water-surface relation, and proportional size of input water drop to its respective input surface area. The residual storage was measured by squeegeeing the water from the surface and then weighing it. The last remaining drops were wiped up with preweighed paper toweling. The toweling was again weighed and the difference added to the amount squeegeed from the surface for the total amount, which was then converted to a volume. The measurements indicated a tendency for decreased residual storage for successive tests. This trend of progressive wetting developed even though the surface was wet thoroughly before the first test and then wiped dry after each test.

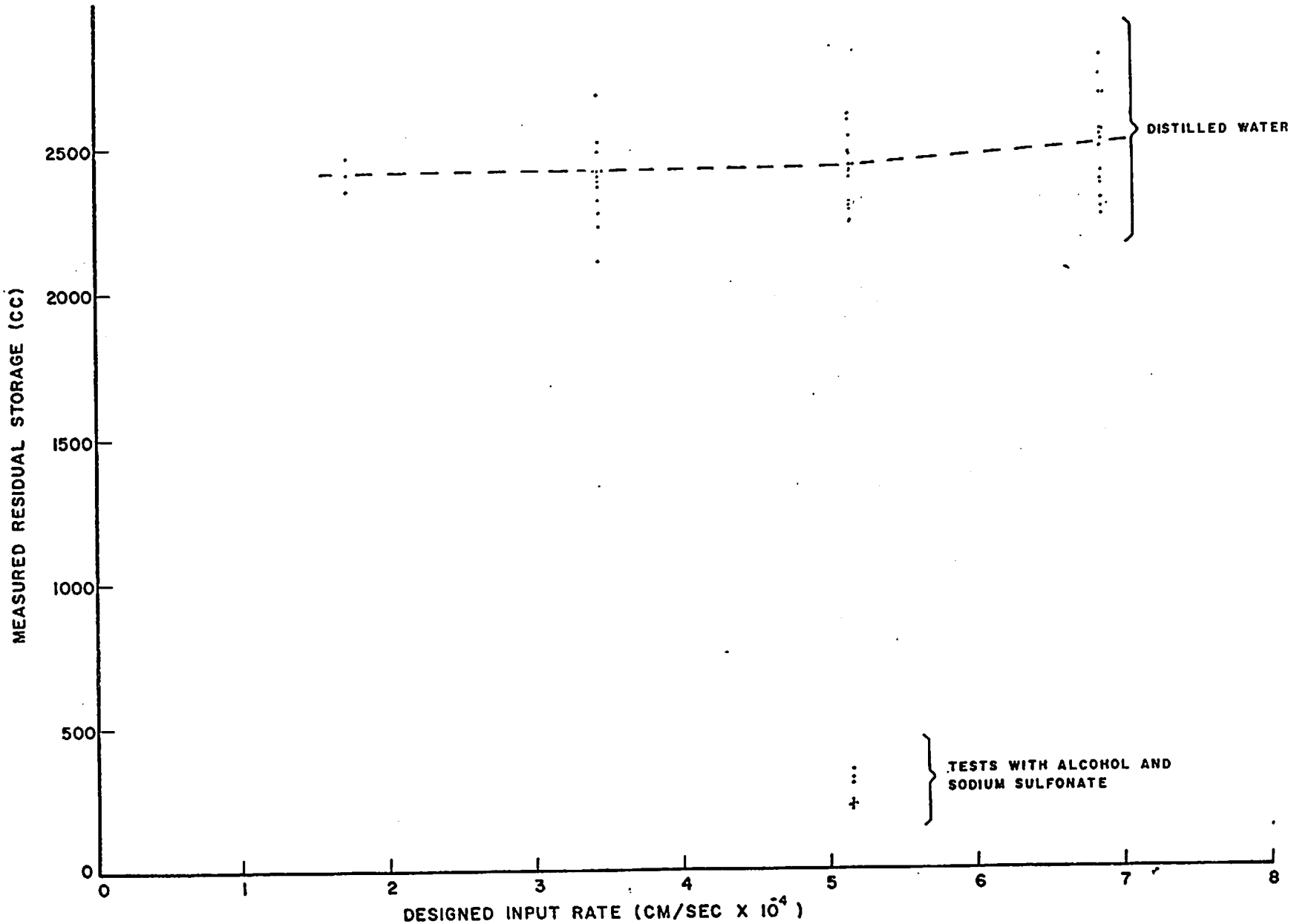


FIGURE II. MEASURED RESIDUAL STORAGE (AMOUNT OF LIQUID REMAINING ON THE MODEL SURFACE AFTER DRAINAGE WAS COMPLETE) VS. INPUT RATE.

This problem of initial surface condition may also be compounded by changes of the environment about the surface -- temperature, humidity, etc. The peculiar water-surface interaction, already mentioned, is further reflected in the instable storage situation. A slight jarring of the model would cause additional water to roll off the surface. The water was dropped on the surface from tubes spaced 2 inches on centers; thus one tube supplied the input to 4 square inches of model surface. Since the water did not spread evenly over the surface, it is possible that different distributions of water occurred on the surface with each test which, in turn, caused different residual storages.

As might be expected, the time to the beginning of outflow and time required to establish equilibrium outflow both decreased as input rate increased. Figure 12 illustrates these relations.

Linearity of the laboratory system: There is general interest in the linearity of hydrologic systems, and this curiosity is extended to the laboratory system. One may already have some suspicions that the laboratory system, in the range of the reported tests, is nonlinear because of the storage relations reported in Figures 6-10. But this question can be pursued further. If a system is linear, then the relation between the input and output is one to which the principles of superposition and proportionality apply. Both principles are used to inspect, cursorily, if this laboratory system is linear.

When attempting to apply the principle of superposition, an immediate difficulty was encountered. The outflows of the laboratory system were given as responses to the total input which involved a time delay. No attempt was made to generate an input minus storage (rainfall

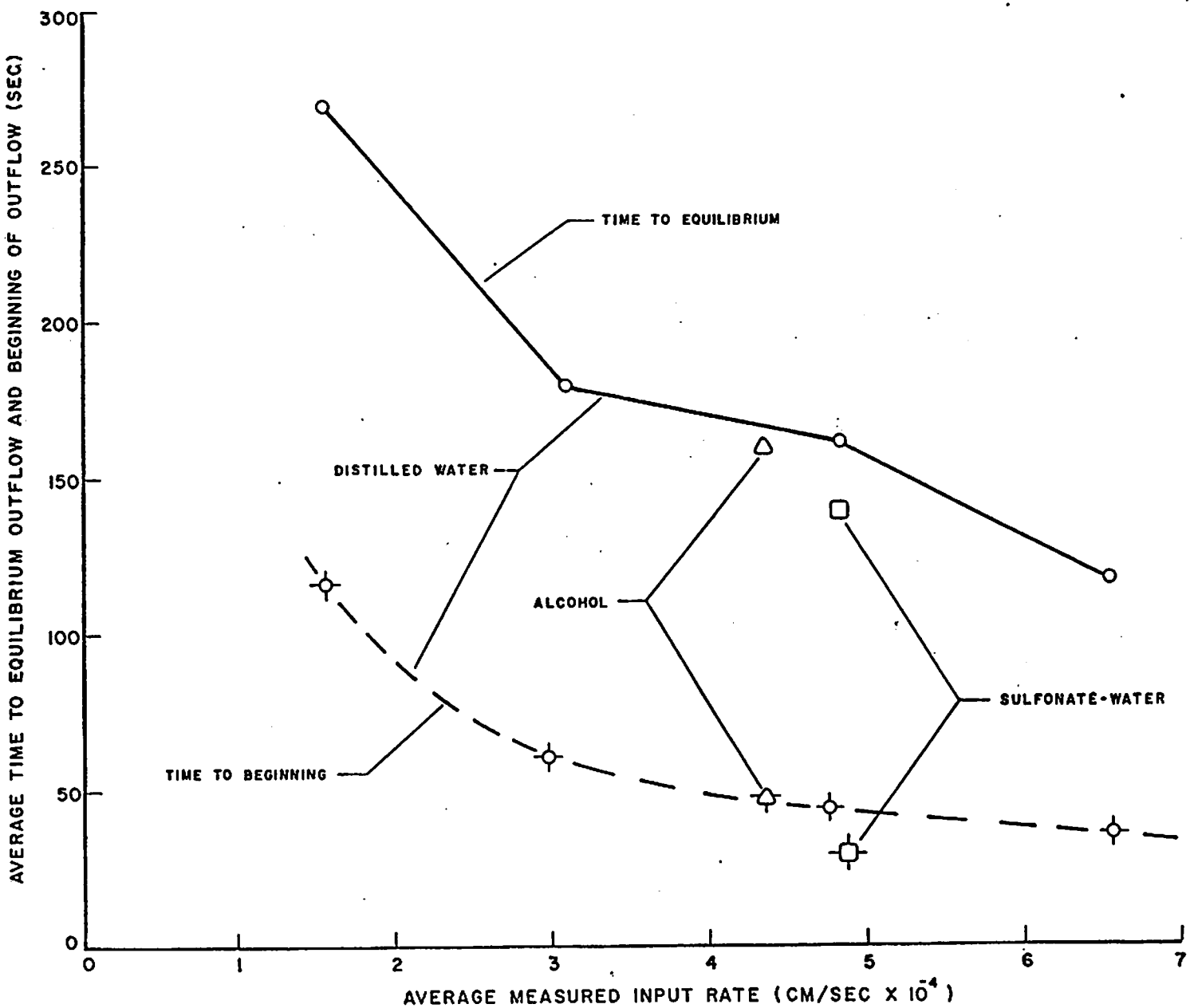


FIGURE 12. TIME TO ESTABLISH EQUILIBRIUM DISCHARGE AND TO BEGINNING OF OUTFLOW (STARRED POINTS) VERSUS INPUT RATE.

excess) to which, traditionally, the outflow response is immediate (no time delay). The average delay time of the responses to the 6.88×10^{-4} -cm/sec input of water was 36 seconds. For purpose of this cursory inspection, the duration of the input was taken as the time from the beginning of the outflow to the end of the input pulse. For the 70-second pulse the "effective duration" was taken as 34 (70-36) seconds.

To develop linear responses, the 70-second response (34 seconds effective duration) was repeated every 34 seconds from the beginning of the outflow, and ordinates of the overlapping responses summed to give the response at 68, 102, 136 seconds, etc. beyond the beginning of the outflow. Thus, by the summing method, the response to a 102-second input is the nearest that can be generated to compare with the 100-second pulse. See Figure 13 for the comparison. The response of the 40-second pulse was not considered as an elementary summing unit because it was almost no response, representing an effective input of about 4 seconds.

Another approach is to subtract offset equilibrium responses. By offsetting two of these total response curves by the length of a desired input period and subtracting the curve at the end of the period from the initial curve, the desired response is theoretically obtained. These results are also illustrated in Figure 13. Results by the differencing method were, in general, encompassed by the measured responses; whereas, the summed responses encompassed the measured responses.

The same superposition principle was applied to the results of the tests with alcohol. For these tests, the "effective duration" was taken as 22 seconds (70-second pulse duration less the average 48-second delay time to beginning of the outflow). Again, the measured responses

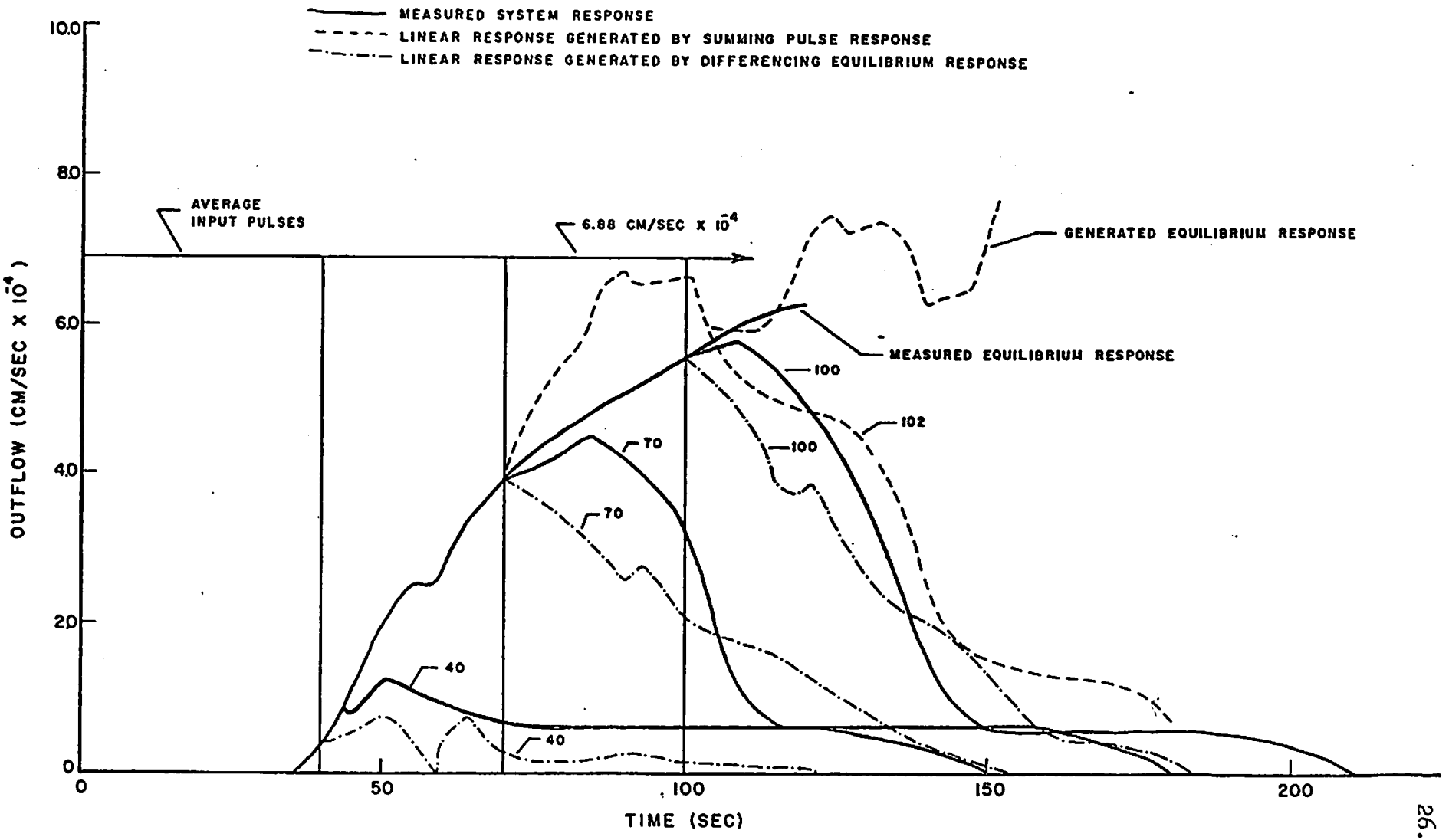


FIGURE 13. COMPARISON OF GENERATED LINEAR RESPONSES WITH MEASURED RESPONSE OF THE LABORATORY CATCHMENT SYSTEM USING DISTILLED WATER.

of the system do not conform with those predicted by the linear methods (Fig. 14). The disparity is less in this case than that which resulted with the water tests. This situation may be interpreted as the more damped the laboratory catchment system is, the more amenable it is to linear representation. This indicates another trend of thought which might bear further investigation.

Figure 15 illustrates what is obtained when the principle of proportionality is applied to the outflows from the 6.88×10^{-4}-cm/sec inputs. The measured outflows from the 6.88×10^{-4}-cm/sec inputs were reduced by three-fourths and compared with the responses from the 5.16×10^{-4}-cm/sec inputs. Again the system demonstrates its nonlinearity. This comparison also illustrates the advancing of the beginning of outflow and the forward translation of the rising portion of the outflow response with respect to increased input rate.

Comparison of laboratory system with the natural system: Since the original objective of this project was the modeling of a natural watershed system, it is interesting to compare the laboratory system responses with those of the natural system. For this comparison, records of five prototype watershed runoff events, between 1939 and 1945, were selected as representing a range of outflow responses in the natural system. Records for the years after 1945 could not be used, because the boundary of the natural watershed changed (man-made terraces determining a portion of the boundary failed). The laboratory catchment was a model of the original shape of the watershed. The input, outflow, and storage relations of these five events are given in Figures 16, 17, 18, 19, and 20.

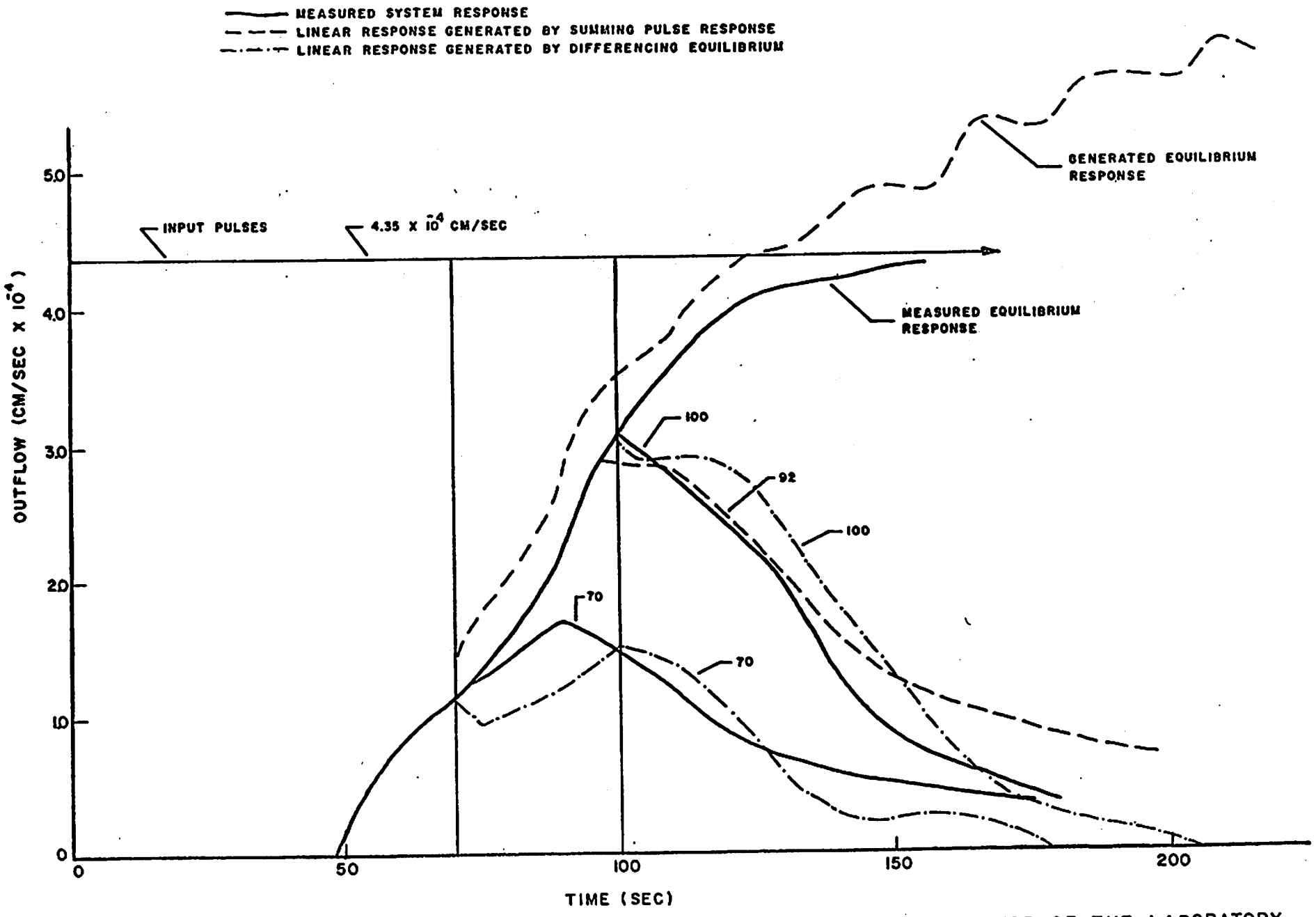


FIGURE 14. COMPARISON OF GENERATED LINEAR RESPONSES WITH MEASURED RESPONSE OF THE LABORATORY CATCHMENT SYSTEM USING ALCOHOL.

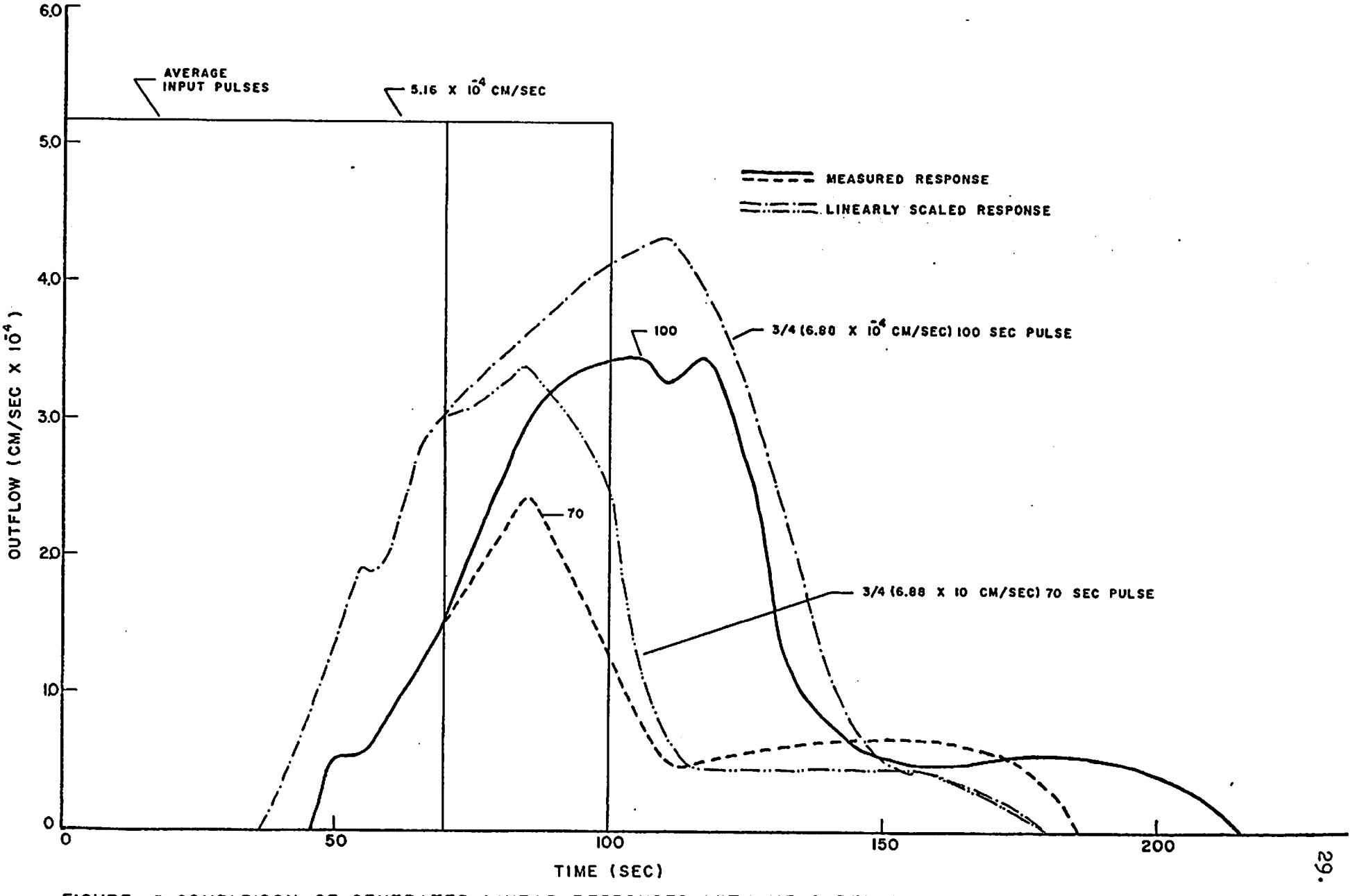


FIGURE 15. COMPARISON OF GENERATED LINEAR RESPONSES WITH MEASURED RESPONSE OF THE LABORATORY CATCHMENT SYSTEM USING DISTILLED WATER.

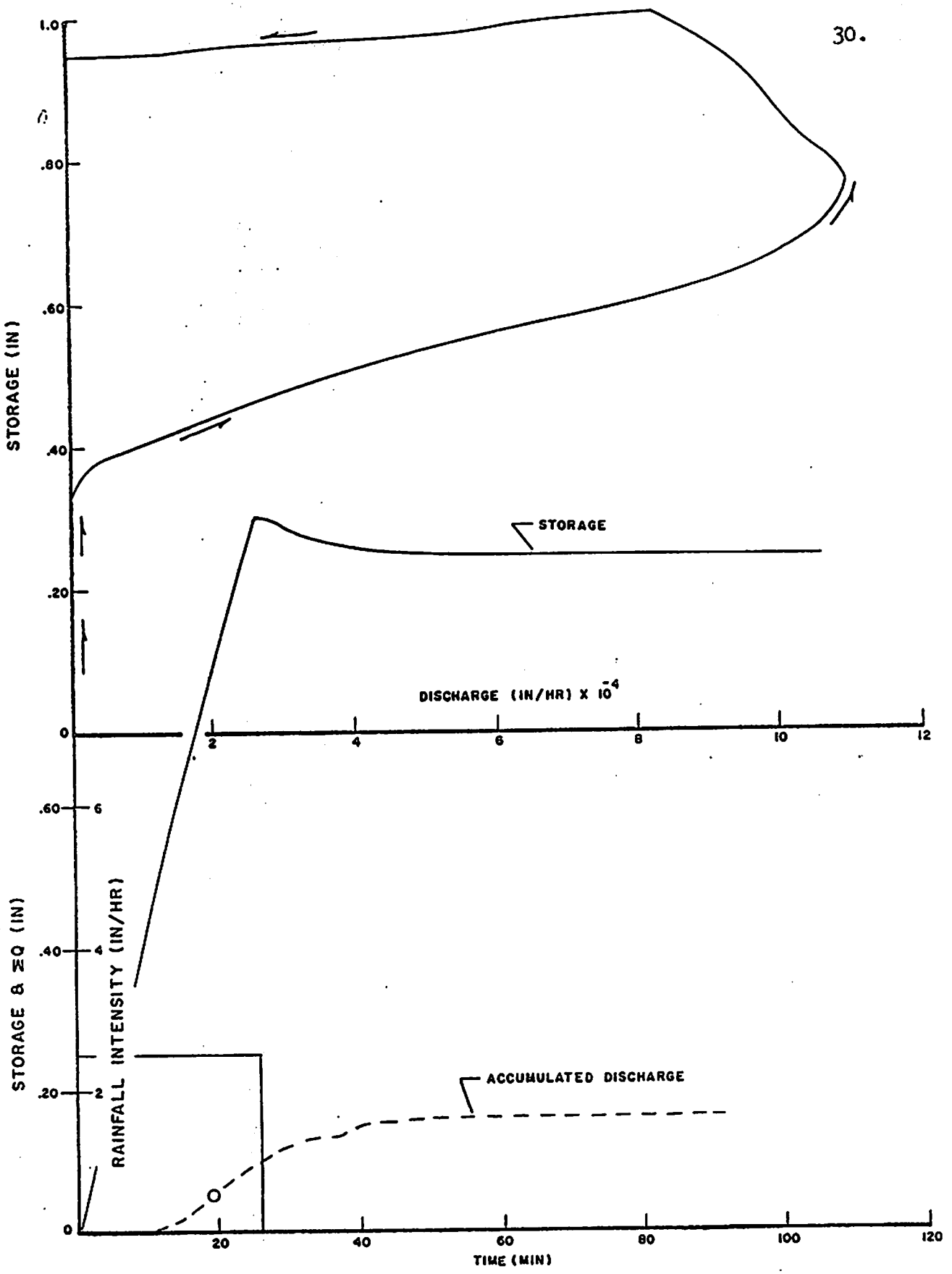


FIGURE 16. EVENT NO. 1 STORAGE VS. DISCHARGE AND TIME, ACCUMULATED DISCHARGE VS. TIME, AND RAINFALL RATES VS. TIME FOR EVENT OF 8/20/40 ON WATERSHED 47.01.

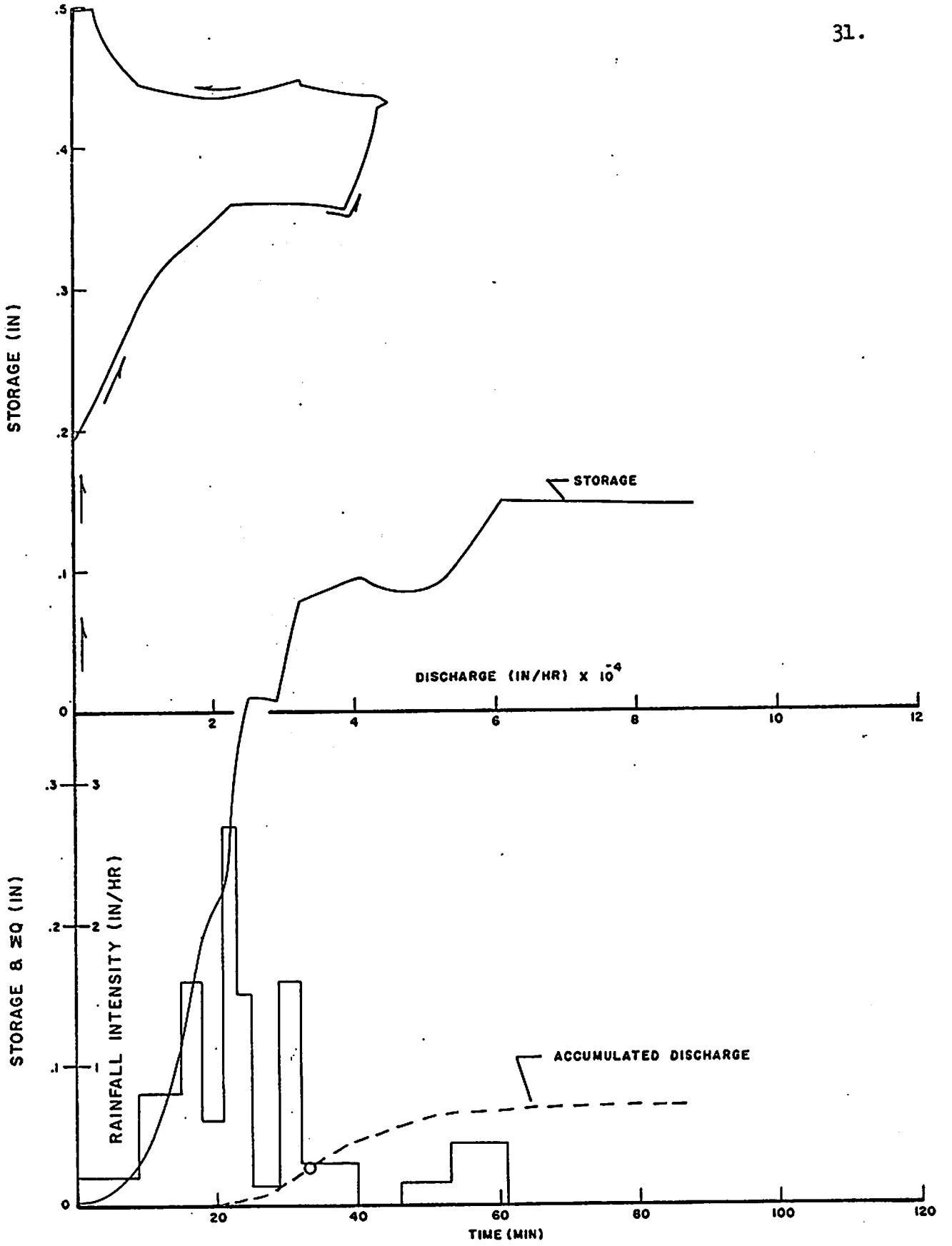


FIGURE 17. EVENT NO. 2 STORAGE VS. DISCHARGE AND TIME, ACCUMULATED DISCHARGE VS. TIME, AND RAINFALL RATES VS. TIME FOR EVENT OF 10/16/44 ON WATERSHED 47.01.

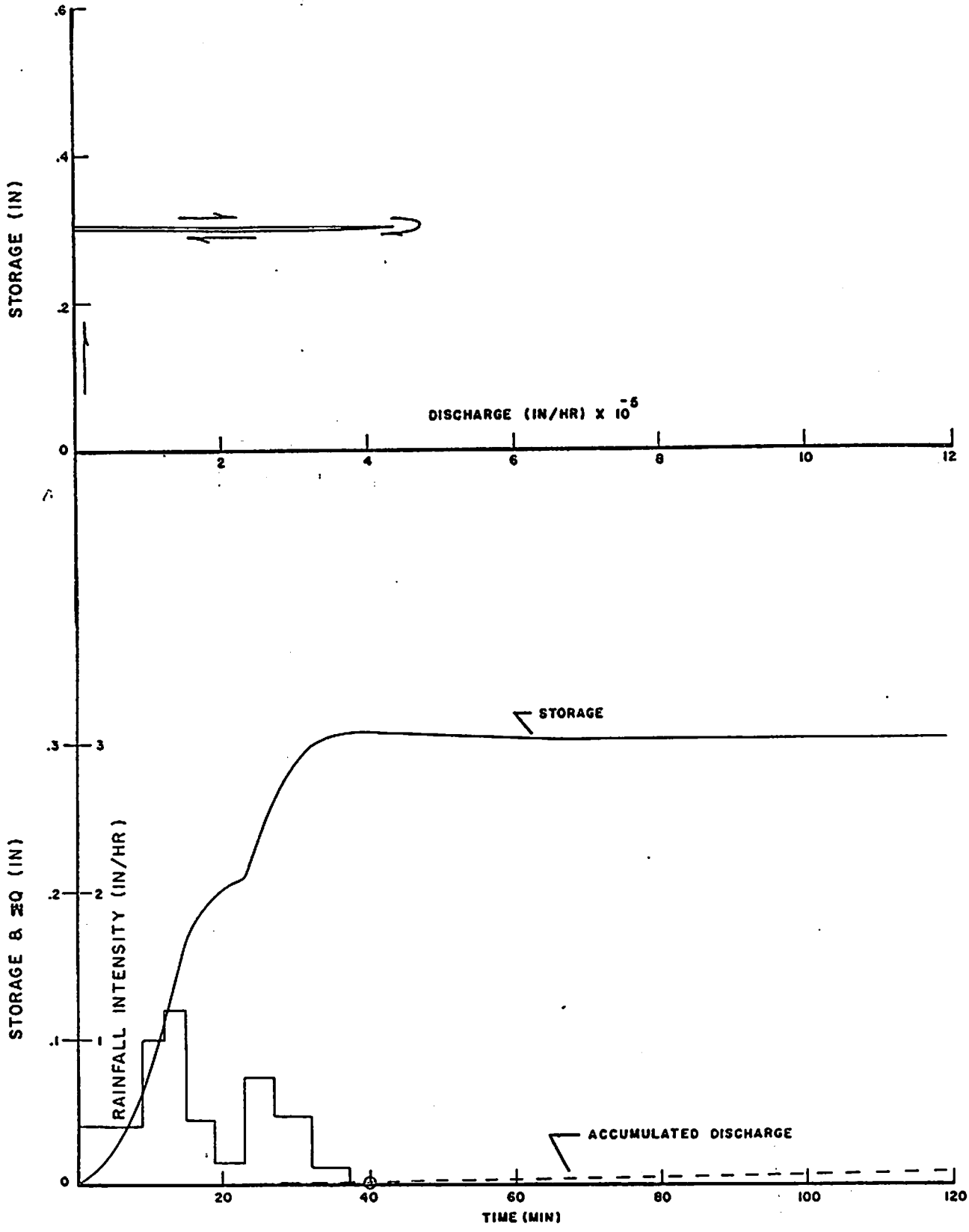


FIGURE 18. EVENT NO. 3 STORAGE VS. DISCHARGE AND TIME, ACCUMULATED DISCHARGE VS. TIME, AND RAINFALL RATES VS. TIME FOR EVENT OF 9/25/39 ON WATERSHED 47.01.

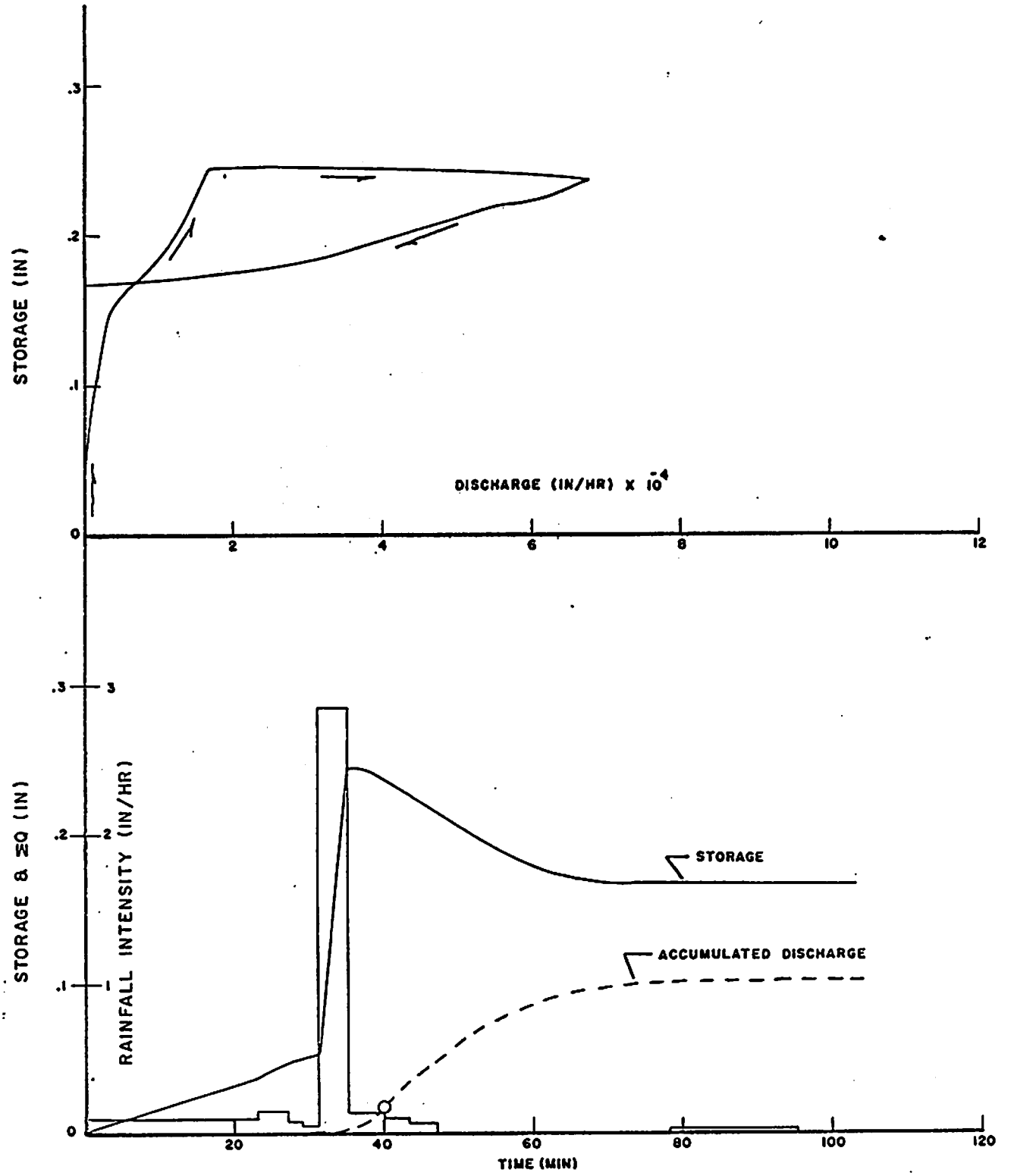


FIGURE 19. EVENT NO. 4 STORAGE VS. DISCHARGE AND TIME, ACCUMULATED DISCHARGE VS. TIME, AND RAINFALL RATES VS. TIME FOR EVENT OF 8/17/44 ON WATERSHED 47.01.

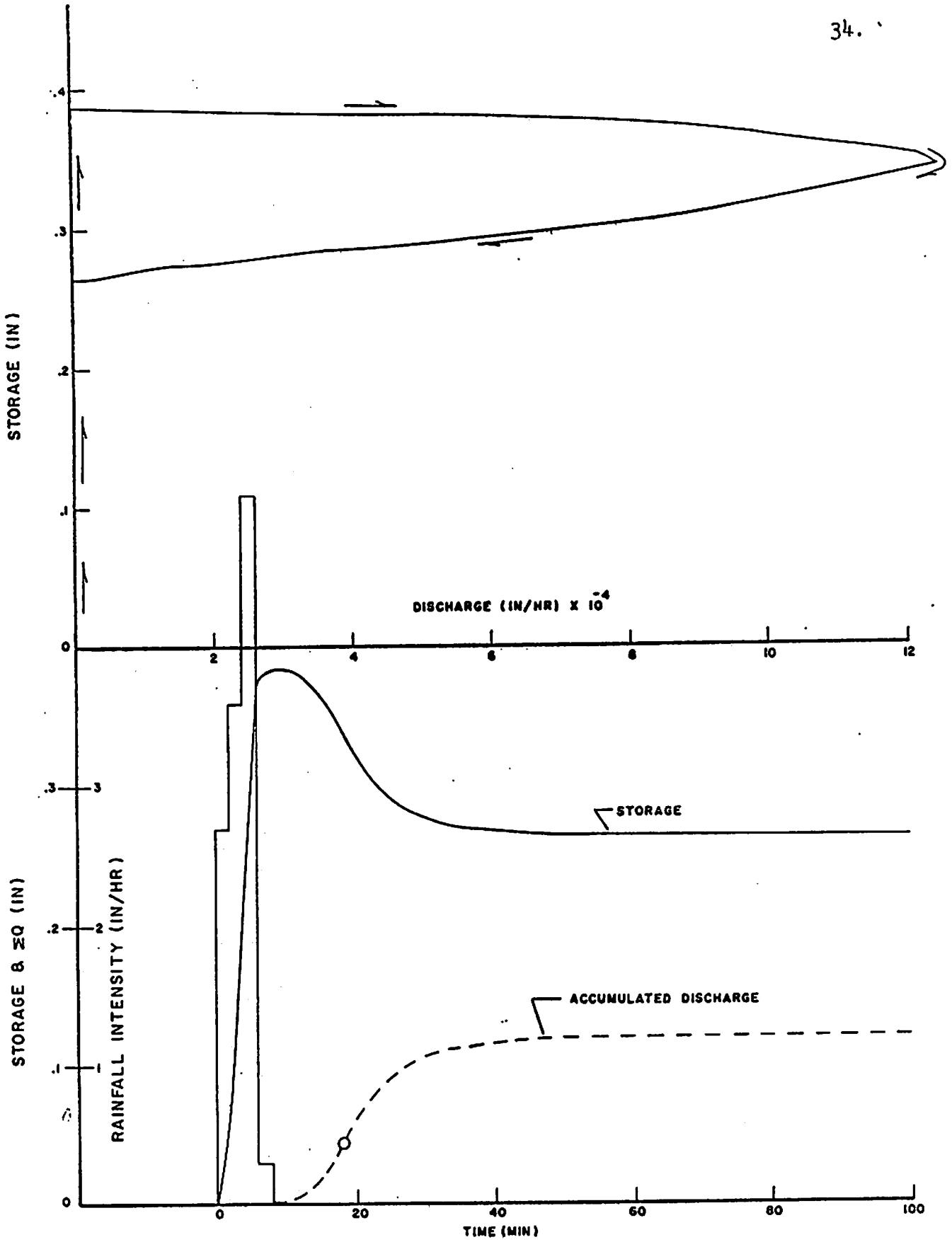


FIGURE 20. EVENT NO. 5 STORAGE VS. DISCHARGE AND TIME, ACCUMULATED DISCHARGE VS. TIME, AND RAINFALL RATES VS. TIME FOR EVENT OF 9/20/41 ON WATERSHED 47.01.

To make a comparison between the outflows of the natural system and laboratory system, normalized cumulative distribution curves for both natural and laboratory outflows, were prepared. These distribution curves for selected model responses are given in Figures 21 and 22. Time-scaled distribution curves for the five natural outflow events are given in Figure 23. The peak of the natural flow event occurred at an accumulated volume of between 18 and 38 percent of the total outflow volume. None of the model outflow results had the peak positioned in this range except the 40-second pulse of water at the input rate of 6.88×10^{-4}-cm/sec. However, the distribution of the 40-second-6.88×10^{-4}-cm/sec response is disproportionally affected by the distinctive hump at the end of the recession which has been previously discussed (Fig. 4). In an effort to get a distribution curve for the laboratory system to compare with the natural system distributions, a line was drawn through and extrapolated beyond the points of peak outflow on the cumulative distributions of the laboratory responses (Figs 21 and 22). This line was used to give a prediction for the time to a peak discharge that occurred at an accumulated discharge of 25 percent of the total discharge. This procedure gave a time to peak of 60 seconds for the 6.88×10^{-4}-cm/sec water tests and 51 seconds for the sulfonate-water mixture tests. Then the outflow responses were visually sketched on the summary plots of outflow rate vs. time, using the estimated peak times and the other response curves to guide the shape of the estimated outflow. The estimated water response is shown in the bottom plots of Figure 4, and the estimated sulfonate-water response is shown in the top plots of

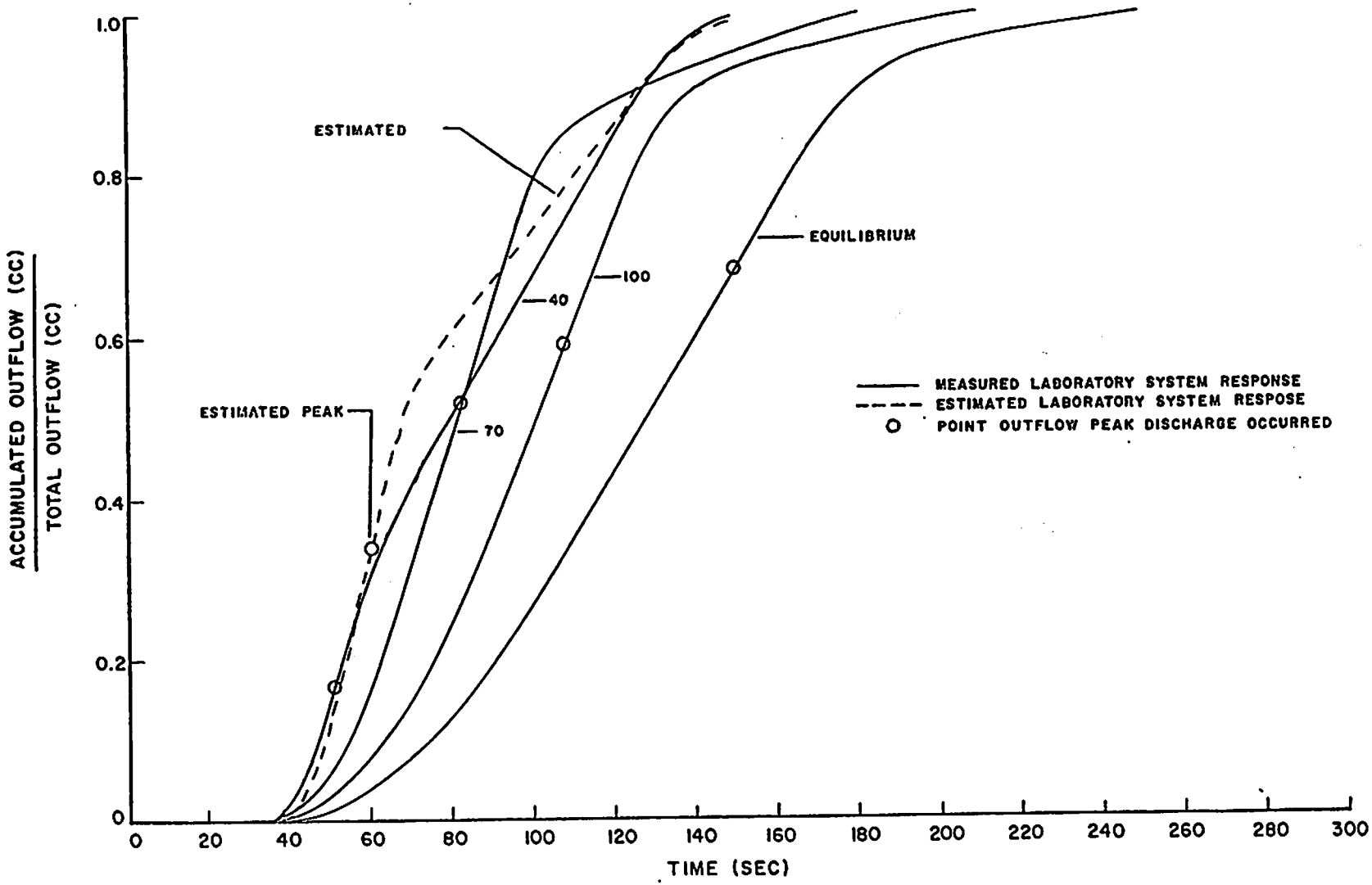


FIGURE 21. NORMALIZED CUMULATIVE DISTRIBUTION FOR INPUT OF DISTILLED WATER AT A RATE OF 6.88 X 10^{-4} CM/SEC FOR DURATIONS OF 40, 70, 100 SECONDS AND UNTIL EQUILIBRIUM OUTFLOW WAS ESTABLISHED. ESTIMATED 60 SECOND RESPONSE (DASHED LINE).

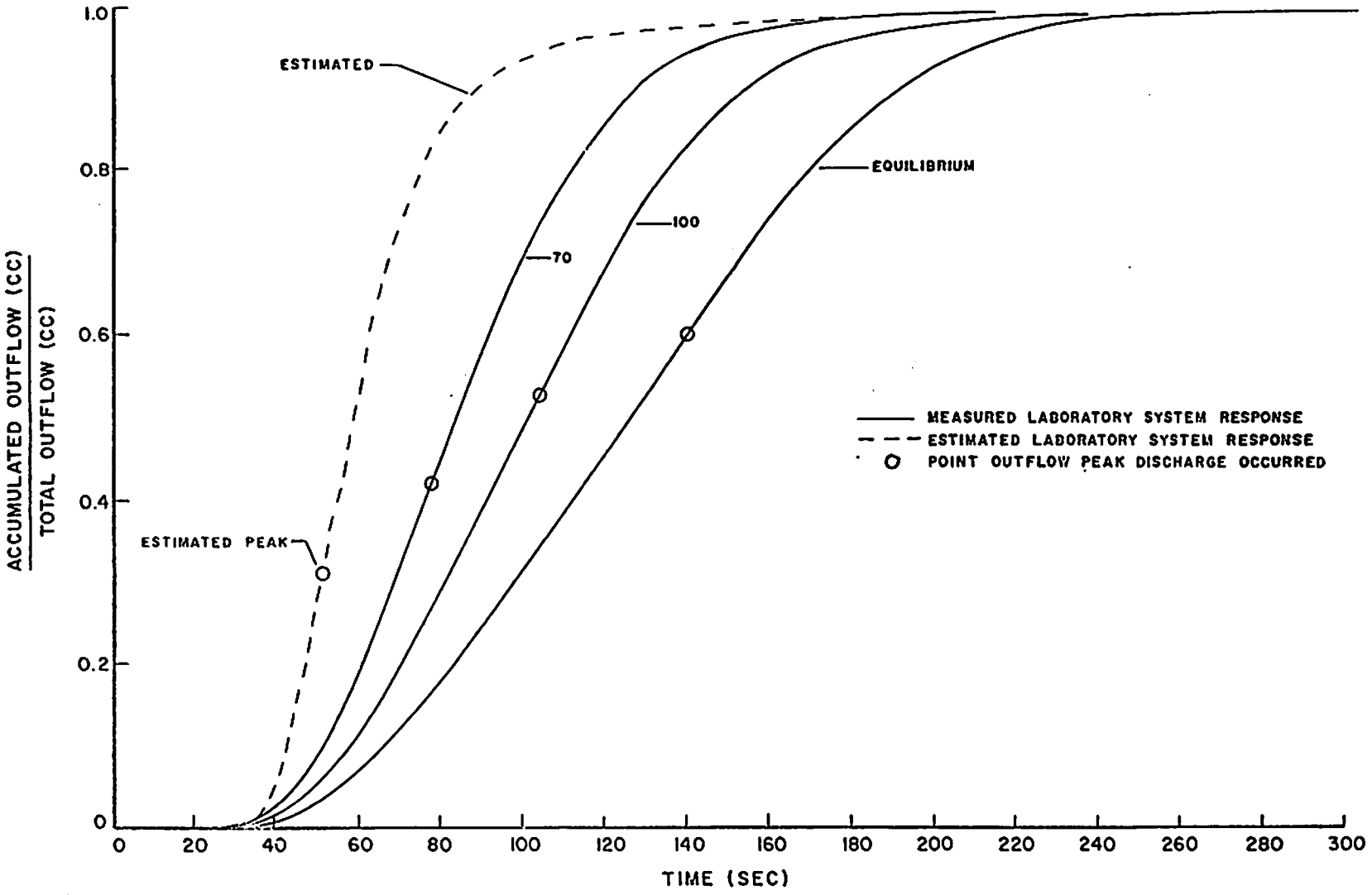


FIGURE 22. NORMALIZED CUMULATIVE DISTRIBUTION FOR INPUT OF WATER-SULFONATE MIXTURE AT A RATE OF 5.16 X 10^{-4} CM/SEC FOR DURATIONS OF 70, 100 SECONDS AND UNTIL EQUILIBRIUM OUTFLOW WAS ESTABLISHED. ESTIMATED 51 SECOND RESPONSE (DASHED LINE).

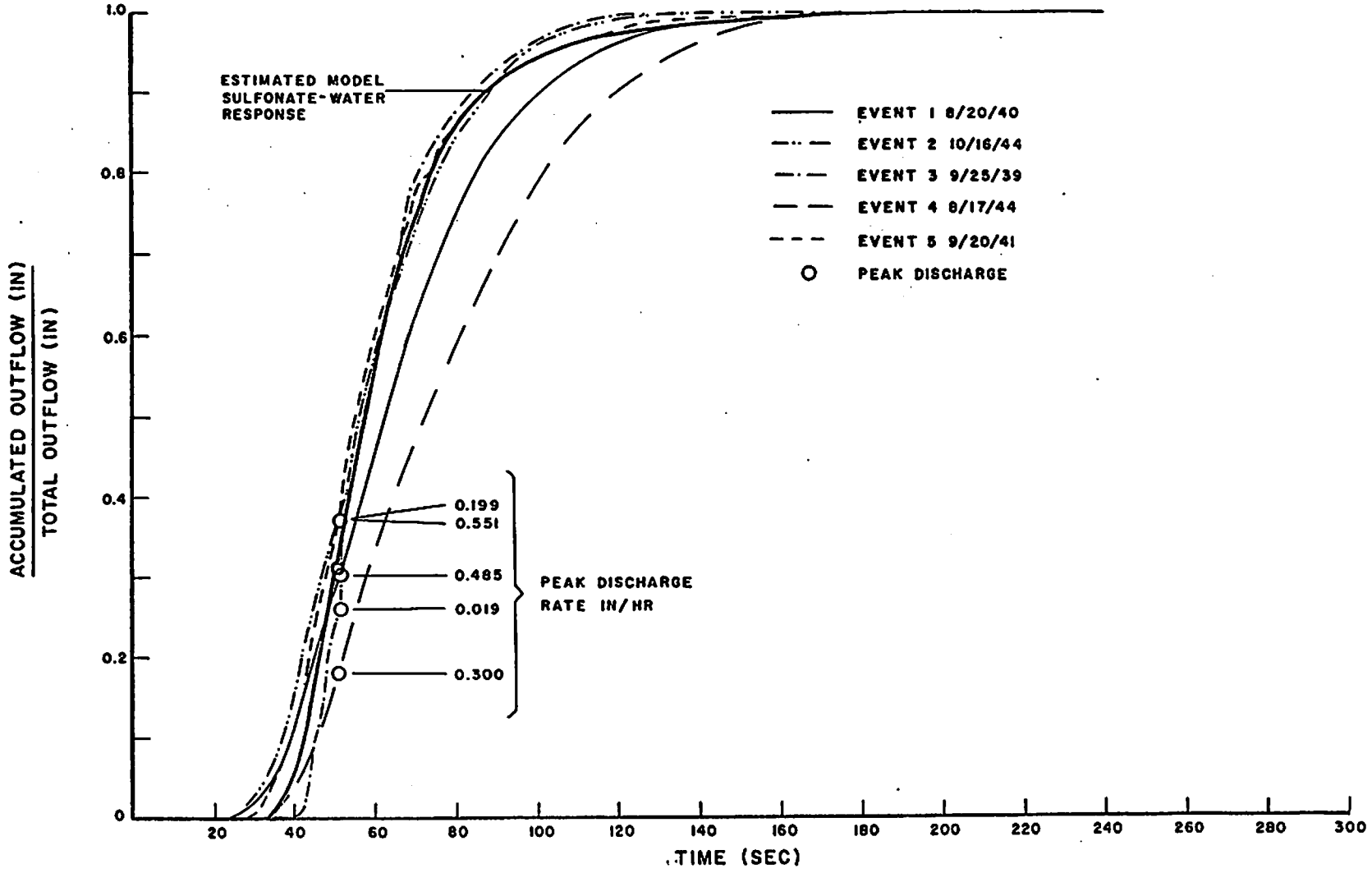


FIGURE 23. COMPARISON OF TIME TRANSFORMED PROTOTYPE CUMULATIVE DISTRIBUTIONS WITH AN ESTIMATED MODEL SULFONATE - WATER RESPONSE.

Figure 5. The cumulative distribution curves of these estimated responses were calculated and are plotted with dashed lines on Figures 21 and 22.

The estimated sulfonate-water response compared better with the time-transformed prototype cumulative distributions than the estimated water response and is shown superimposed on the prototype curves in Figure 23. The scaling factor was formed by dividing the time to peak (in seconds) of the laboratory outflow by the time to peak (in minutes) of the watershed discharge; then the time scale of the prototype cumulative distribution curve was multiplied by this factor to give an adjusted scale in seconds.

The time scale originally proposed in the design of this system was the square root of the length ratio (Chery, 1965):

$$t_r = [L_r]^{\frac{1}{2}} = (175)^{\frac{1}{2}} = 13.25$$

This is also the same ratio as would be predicted by relations developed by Grace and Eagleson (1967) for models of surface-flow with no vertical distortion. A summary is given in Table 2 of the time ratios obtained when the natural events were scaled to compare with the estimated sulfonate-water response. For the natural events, the time to peak was measured from the beginning of the first pulse of appreciable rainfall (greater than .50 in/hr). Low intensity rainfall (less than .40 in/hr) prior to the intense rainfall was disregarded on all events except that of Event No. 5 (noted with an asterisk in the table), which had the time to peak measured from the beginning of rainfall.

Table 2. Time ratios and peak rates for the events of Watershed 47.01 as illustrated in Figure 24

No.	Event date	Peak discharge		Time to peak (t_p)		Time ratio t_r
		cfs	in/hr	min	sec	
1	8/20/40	47.6	0.485	19	1140	22.35
2	10/16/44	19.5	0.199	24	1440	28.24
3	9/25/39	1.9	0.019	40	2400	47.06
4	8/17/44	29.4	0.300	17	1020	20.00
5	9/20/41	54.0	0.551	18*	1080	21.18
Original design time ratio $[L_r]^{\frac{1}{2}}$						13.25

* Time to peak measured from beginning of rainfall. Low intensity rainfall (less than 40 in/hr) prior to the intense rainfall was disregarded on all the other events.

The better comparison between the sulfonate-water response and natural-system responses indicates that the surface tension influences that were evident in the tests with water need to be reduced. Also, there is an indication that an input liquid, such as the sulfonate-water mixture, will give a laboratory system response time distributed more nearly as the natural system response. This tendency needs more extensive investigation before any assertions can be made.

The results also indicate that the shorter duration pulses (less than 55 seconds for the sulfonate-water tests and less than 65 seconds for the water tests) produce responses that more nearly compare with the cumulative volume distribution of the prototype response. This trend is also supported by the progression in the storage versus discharge relations and proportions between storage and accumulated discharge. This is seen when these relations of prototype Events 4 and 5 (Figures 19 and 20) are compared with the shortest duration pulse tests (Figures 6, 7, 8, 9, and 10). In all the laboratory tests except the one with sulfonate-water, a triangular storage versus outflow storage relation was developing with shorter input durations, and the total accumulated outflow was less than the final storage in the system; a proportion the natural system exhibited. Even for the seventy-second pulse of sulfonate-water, the storage-outflow relation was developing a peak storage before the peak discharge relation that could conceivably progress to a triangular shape similar to those of the natural events shown in Figures 19 and 20.

The results from the water tests indicate that the high input rate at the shorter durations gives storage relations that compare with the two natural Events 4 and 5 (Figs. 19 and 20). Thus, I suspect that

distortion (by increasing) of the model input rate will produce laboratory catchment responses similar to some types of natural system responses. The need for increased input rates was also discussed earlier in the paper with respect to surface-liquid interaction.

The reference to a certain type of natural system response introduces another aspect of the problem revealed by the analysis of the natural system outflow (Figs. 16, 17, 18, 19, and 20). Clearly shown are two types, or classes, of storage-discharge relations that appear to be determined by the rate of the input. Events 1 and 2 had relatively lower input rates for longer durations; whereas Events 4 and 5 had essentially single-pulse inputs of short duration and relatively higher input rates (though the 2.85 in/hr input rate of Event No. 4 was only .33 in/hr greater than the 2.52 in/hr input rate of Event No. 1). Event No. 3 appeared to be a threshold (almost no runoff resulted) and a boundary between the two classes; consequently the arrangement of the events. Also, the peak discharge resulting from the high-intensity, short-duration inputs occurred after the input; with the lower intensity, longer duration inputs, the peak occurred at the end or within the duration of the input. Similar results can be observed in the model tests.

These several analogous behaviors between the model system and the natural system, plus the indicated behavior of the laboratory system under inputs beyond the range tested suggest that laboratory systems could be developed to be analogs of natural systems. This possibility is also proposed by Barr (1968). The distinctive storage-outflow relation,

proportionality of total system storage and accumulated outflow, position of peak outflow with respect to the duration of the input and the proportions of the input already appear as criteria in determining a possible analog relation.

SUMMARY AND CONCLUSIONS

These tests illustrated the need for more precise control of the input to the laboratory catchment system. This may be accomplished by technical improvements in the apparatus and, for input systems such as the one used, developing guiding relations as to distribution and placement of the individual streams of input with respect to area and geometrical configuration of the catchment system.

The unsatisfactory performance of water in this particular system was obvious. When a surface tension reducer was mixed with the water, better performance with respect to the liquid-surface interaction and an indication of more similar performance to a prototype watershed were obtained. In the laboratory system, the input rate could have been increased until the geometrical control of the system was submerged. The tests did not span the range of allowable input rates; further, it is apparent, they were near the low end of that range.

The response of the laboratory system was nonlinear. This was demonstrated by the fact that neither the principle of superposition nor the principle of proportionality could give generated responses that would compare with the actual responses.

The results indicated that more information about the system response could be derived from inputs of higher rates and shorter durations.

Responses from greater input rates and shorter pulse duration tended to be more nearly time distributed and have storage relations similar to the prototype system responses. This performance suggests directions for investigations of the criteria for physical hydrologic analogs.

To what extent laboratory catchment systems can be analogs of, or representatives of, natural watershed systems is an intriguing question. Further, they have definite potential as an assistance in developing mathematical models of natural watershed systems.

REFERENCES CITED

Barr, David I. H. Discussion of "Scale model of urban runoff from storm rainfall," J. Hydraulics Div., ASCE, 94(HY-2:586-588, 1968.

Chery, D. L., Jr. Construction, instrumentation, and preliminary verification of a physical hydrologic model, M.S. Thesis, Utah State University, Logan, Utah, 152 pp., 1965.

Chery, D. L., Jr. Design and tests of a physical watershed model, J. Hydrology 4(3):224-235, 1966.

Grace, Robert A., and Peter S. Eagleson. Scale model of Urban runoff from storm rainfall, J. Hydraulics Div., ASCE, 93(HY-3): 161-176, 1967.